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September 2018

**Report**
Coastal protection technologies in a Danish context

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**Cover photo**
Recreational path on the lolonian dike (Det Lollandske dige). Photo: Eva Sara Rasmussen, 2018

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## Preface

This project was financed by the innovation network “Water in urban areas” (in Danish: “*Vand i Byer*”). It was carried out in the period July 2017- June 2018 by a working group involving the Technical University of Denmark, Copenhagen University, Gottlieb Paludan Architects and Region Hovedstaden.

## Abstract in English

Recent storm surge events along with the discussions on climate change and sea level rise make coastal protection a pertinent issue in Denmark. The purpose of this report is to analyse past and present coastal protection strategies in Denmark and use this as a baseline for a critical reflection on current practice and possible ways forward. The report is divided into three main parts. First, the study provides a state of the art on coastal protection technologies in Denmark and internationally. Second, we propose a framework for working with coastal protection. Third, four selected case studies are analysed in detail (i.e. Køge Bugt Strandpark, Nordkystens Fremtid, Vejle, and Gyldensteen Strand) using a multi-criteria assessment framework. The key findings include the prevalence of hard structural protection technologies such as sluice gates and dikes (24 of 32 reviewed projects in Denmark); the need to analyse and frame coastal regions with a view to the level of economic, social and technical complexity and capacity; and the need to go beyond coastal protection as a technical discipline and strive for holistic solutions with an emphasis on innovation and the collaborative and explorative process of planning, designing and implementing coastal protection measures in a sustainable manner. This report aims to spark a discussion on coastal development and highlights some of the key challenges and tasks that need to be addressed in the years to come to achieve the best possible outcome.

## Resumé på dansk

De seneste års stormflodshændelser og diskussionen om klimaforandringer og globale havvandsstigninger er med til at gøre kystbeskyttelse et mere og mere aktuelt emne i Danmark. Formålet med denne rapport er at analysere historiske kystbeskyttelsesstrategier og bruge dette som et fundament for en kritisk refleksion over dansk praksis og mulige veje fremadrettet. Rapporten er inddelt i tre hovedafsnit. Først præsenteres en gennemgang af kystbeskyttelsesteknologier i Danmark og i en international kontekst. Derefter foreslås en metode til at arbejde med kystbeskyttelse, hvorefter fire udvalgte projekter (Køge Bugt Strandpark, Nordkystens Fremtid, Vejle, and Gyldensteen Strand) analyseres ved brug af en multikriteriemetode. Hovedresultaterne er, at hårde kystsikringsteknologier som sluser og diger er dominerende i Danmark (24 ud af 32 gennemgåede projekter), at det er relevant at analysere og differentiere kystområder ud fra deres økonomiske, sociale og teknologiske kapacitet og kompleksitet, og endelig at der er behov for at se kystbeskyttelse som mere end en teknisk disciplin og derfor stræbe efter helhedsorienterede løsninger med fokus på innovation og en samarbejdsorienteret proces omkring planlægning, design og implementering af bæredygtige kystbeskyttelsesløsninger. Denne rapport har til formål at starte en debat om kystudvikling og fremhæver nogle af de væsentligste udfordringer og opgaver, der skal adresseres i de kommende år for at løfte opgaven på bedst mulig vis.

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## List of abbreviations

| | |
|---|---|
| **CE** | Coastal erosion |
| **CPT** | Coastal protection technologies |
| **H** | Historical coastal protection intervention (implemented between the year 1500-2000) |
| **ICZM** | Integrated Coastal Zone Management Principles |
| **R** | Recent coastal protection intervention (after the year 2000) |
| **RSLR** | Relative sea-level rise |
| **SLR** | Sea level rise |
| **SS** | Storm surge |

# 1. Introduction

## 1.1. Problem identification

Denmark has a land area of about 42,925 $km^2$ and a coastline of 8,750 km (Danmarks statistik, 2017; DR, 2014), of which almost 1,800 km are protected by dikes or other permanent technical installations (Danish Ministry of the Environment, 2005). Besides having a very long coastline, Denmark is also affected by climate change in terms of an increase in storm surge events, sea level rise and an increase in heavy rainfalls (Arnbjerg-Nielsen, 2006).

In Denmark, a mean **sea water level rise** between 0.3m and 0.6m is expected by the year 2100 (**Fig. 1**). The increase in sea level consequently affects the maximum water level during a storm surge event. On the West Coast of Jutland, an increase of maximum water level with extreme storm surge events between 0.2 and 1.5 m is expected.

**Storm surge** is an abnormal rise in seawater level caused by the combination of tide, air pressure, and storm's wind pushing onshore (NOAA 2017; Rambøll, 2015). Historically, the most severe storm surge events occurred predominantly in the southwest coast of the Jutland peninsula (Rambøll, 2015). Denmark has been experiencing an increase of storm surges in the recent years (*Bodil* in 2013, *Egon* in 2015, *Urd* in 2016) which affected not only the west coast but also the Zealand Island (Københavns Kommune, 2017).

In Denmark, additionally, the expected increase in **extreme rainfall events** could be particularly relevant for coastal cities if a combination of storm surges, increased sea level, and heavy rainfalls occur concurrently. The combination of these events could severely heighten the risk of flooding in the coastal cities. An example of an urban system challenged by these types of event is the city of *Vejle* (south-east Jutland).

Additionally, **coastal erosion** is another phenomenon affecting significantly the Danish coasts. Erosion can be defined as removal of material from the coast by waves and tides, causing coastal retreat (BGS, 2012). Coastal erosion in Denmark is a severe problem especially in the northwest coast of Jutland (up to 4 m/year) and the north coast of Zealand (Miljø og Fødevareministeriet, 2016).

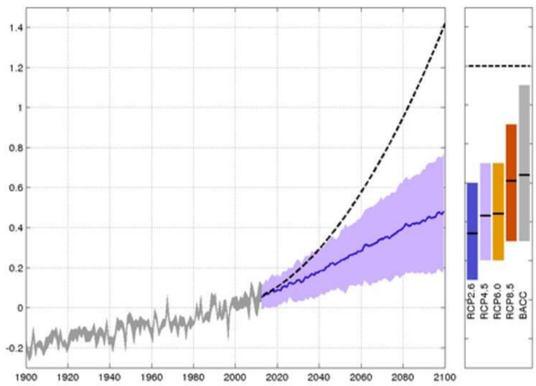


***Fig. 1.*** *Absolute mean sea water level in Denmark in the period 1900-2100 (Miljøstyrelsen, 2015)*

## 1.2. Designed risk areas in Denmark

An analysis carried out by COWI (2017) investigated the areas at risk in Denmark, considering coastal cities with more than 10,000 inhabitants. The results identified that 33% of damages costs will occur in the capital region of Copenhagen if actions are not taken (COWI, 2017). This corresponds to damage costs between 5 and 35 billion dkk. Ten areas with special risk have been identified by the Danish Coastal Authority, including the coastal towns of *Juelsminde*, *Vejle*, *Fredericia*, *Aabenraa*, *Korsør* and *Nakskov*, as well as the wider coastal regions along *Randers Fjord*, *Odense Fjord* and *Køge Bugt* (Miljøministeriet og Transportminiteriet, 2011).

## 1.3. Danish coastal typologies

The Danish coastline is characterised by a heterogeneous coastal landscape. The understanding of landscape variation and characteristics may help in designing technologies which better fit the urban environment. COWI (2017) classified the main elements of the coastal landscape in Danish cities according to how they might be affected by storm surge. Four coastal typologies are presented (**Fig. 2**):

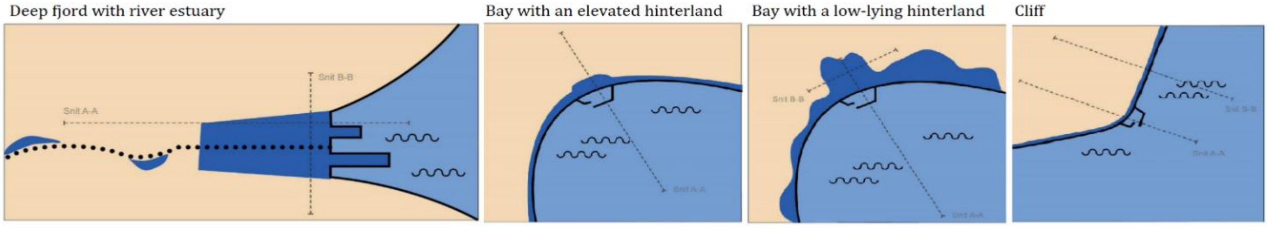


***Fig. 2.*** *Coastal typologies in relation to storm surge type (source: COWI, 2017). From left to right: Type 1-Deep fjord with river estuary (in Danish Tragten);* Type 2-Bay with elevated hinterland (in Danish *Skålen*); Type 3-Bay with low-lying hinterland (in Danish *Den diffuse skål*); Type 4: Cliff (in Danish *Forhøjningen*)

The Danish coastal cities with a typical fjord structure (type 1) are challenged by flooded harbours and flooded industrial or residential areas which are located at low elevation. Additionally, a river from the hinterland could challenge the urban system by causing other potential floods during extreme rainfall events. 24 urban areas have been defined as a fjord structure, of which 15 have a river in the hinterland. An example of type 1 is the city of Vejle.

In the coastal cities with a bay with elevated hinterland (type 2), the floods occur locally and close to the shore as seen in 21 cities including Roskilde.

The cities with a low-lying hinterland (type 3) are characterized by coastal floods which spread in the hinterlands and with the risk of inundating a wider area of low-lying settlements. Twenty-one cities can be classified as type 3, an example is Køge.

Cities with a cliff typology (type 4), are characterized by coastal floods which occur locally (e.g. on a beach road) where the buildings in the front are exposed to higher risks of flooding. Seven Danish cities are classified as type 4 including Elsinore.

## 1.4. Safety levels

The safety levels which a protection technology should meet, are based on risk assessments including predicted sea level rises and storm surge events, and in specific cases, this analysis is combined with predicted rainfall extremes. The City of Copenhagen recommends that new buildings and infrastructures are secured for a 100-year storm surge at 2.63 m (Københavns Kommune, 2017); whilst the new Copenhagen metro is designed to withstand a 2,000-year rainfall event and a 10,000-year storm surge event (Miljø- og Fødevareministeriet/Miljøstyrelsen, 2018).

## 1.5. Coastal protection as one of three approaches to coastal zone management

A widely used framework for coastal zone management is based on three key principles (Wong et al. 2014): protection, accommodation, and managed retreat. ***Protection*** includes hard structures such as dikes, sea walls and floodgates as well as soft structures such as sand dunes, revegetation and sand nourishment or a combination of these options. The key purpose is to protect existing and future developments and assets from coastal erosion and inundation, and hence to minimize impact costs deriving from storm surges, sea level rise and coastal erosion through the investment in protection measures. Protection measures are usually located on or close to the coastline with a view to 'holding the line', but they can also be 'moved seaward' as new structures located offshore (RISC-KIT, 2018) (**Fig. 3**). ***Accommodation*** implies the continued use of land in flood-prone areas adapted to changing conditions e.g. by elevating dwelling floor levels, installing evacuation measures or changing agriculture to aquaculture. ***Managed retreat*** refers to the (planned and gradual) abandonment of sites prone to erosion and flooding and the avoidance of new developments in flood-prone areas.

## 1.6. Research objectives and structure of the report

The purpose of this report is to:

1. Trace the predominant trends in coastal protection technologies in Denmark and in an international context;
2. Propose an integrated framework to assess and work with coastal protection in Denmark;
3. Analyse selected coastal development initiatives in Denmark with a view to holistic coastal management;
4. Discuss the potential limitations of current practices and outline future needs for research and development to better inform the planning and management of coastal areas in Denmark.

This report is divided into three main chapters. Each chapter addresses one of the four objectives stated above. The four chapters can be read separately or in consecutive order.

Chapter 2 provides a structured review of 32 Danish and 19 international coastal protection projects categorised as hard structural coastal protection, softer landscape based protection, a combination of hard and soft protection, and non-structural measures including temporary mobile solutions and a planned retreat from the coastal zone.

Chapter 3 provides an integrated framework to analyse and work with coastal development at the regional and local levels with an outset in the level of social, economic and technical capacity and complexity in the coastal area at hand.

Chapter 4 elaborates on Chapter 3 by providing a multi-criteria framework for the assessment of coastal protection projects encompassing three quantitative aspects (i.e. the level of technical security, economic impact, environmental impact) and two qualitative aspects (i.e. the level of innovation and the aesthetic impact on the coastal landscape). The framework is applied in the review and assessment of four coastal development projects in Denmark, i.e. the already constructed projects at Gyldensteen Strand and Køge Bugt Strandpark as well as the planned coastal protection initiatives in Vejle and along the north coast of Zealand.

Chapter 5 is a critical discussion of coastal protection technologies in the light of climate change and the scale of investment and innovation needed to achieve long-term sustainable outcomes. A key point is to aim for holistic solutions and to facilitate a process of change and the wider systemic level.

Please note that a thorough quantitative analysis of the selected cases and the impacts of coastal protection was not included in this study.

# 2. The state of the art of coastal protection technologies

This chapter focuses on coastal protection and investigates the evolution of coastal protection technologies (CPT) historically and recently implemented in Denmark. A review of the state of the art of CPT realised in an international context is also carried out. The purpose of this is to trace the predominant trends in coastal protection technologies in Denmark and put these trends into an international context.

## 2.1. Methodology for the structured review

The state of the art of CPT is built primarily on the report "Investigation about adaptation to sea level rise" (Rambøll, 2015), which reviewed the main CPT used in a Danish context and provides relevant experience from Holland, England and the United States. Additional information was found in COWI (2017) and Rambøll (2017). Description of cases is also compiled through an extensive online search, a survey among participants in the 'VIB *stormøde*' on 19 September 2017, professional presentations from VIB *stormøder*, and personal interviews with selected stakeholders. The review is not meant to be an exhaustive list of coastal protection projects in Denmark and beyond. Rather it serves to be indicative of the major trends in the approach to coastal protection.

Both Danish and international CPT have been firstly classified by distinguishing them into:

- **Historical**: technologies implemented before the year 2000;
- **Recent**: technologies implemented between the year 2000 and 2017 (year of the study);
- **Pipeline**: technologies which are planned to be implemented after the year 2017.

Rather than a catalogue of technologies, our review presents chronologically the coastal protection ***interventions*** developed in each of the three above-defined periods in Denmark and in the international context. As such, for each coastal protection intervention, the type of technology implemented is listed and discussed. This also means that a coastal protection project carried out over a defined time span might implement the same coastal protection technology in different locations and in different years, and hence can be reported more than once (e.g. system of dykes at the Wadden Sea; Delta works in the Netherlands or a simple dike reinforcement of an existing dike installation).

Of each reviewed coastal protection intervention, the following information was reported:

1. the type of problem addressed;
2. the type of technical solution;
3. the spatial location;
4. year of implementation.

The type of problem which is addressed by the coastal protection intervention follows the definitions provided in section 1.1, namely in relation to storm surge (SS), sea level rise (SLR), coastal erosion (CE). Additionally, some installations might be implemented for the need of land (land reclamation), or for improving navigation in a fjord area. These two aspects were also highlighted.

The distinction between the different types of technology is carried out by following the classification in Table 1.

***Table 1.*** *Classification of coastal protection technologies.*

| Hard solutions | Soft solutions | Combination | Non-structural solutions |
|---|---|---|---|
| Dikes | Sand dunes | Beach Park | Mobile barriers |
| Seawalls | Sand nourishment | | Sand tubes |
| Groynes | Revegetation | | Water tubes |
| Breakwaters | Terps | | Managed retreat |
| Rock walls | | | |
| Sluices | | | |
| Elevated buildings | | | |

The technical solutions were distinguished between structural and non-structural solutions. The structural solutions include a range of hard solutions, soft solutions, or a combination of both; while non-structural solutions involve temporary solutions such as water/sand tubes and mobile barriers, and a 'managed retreat' approach. Hard protection technologies reflect structural engineering. Soft solutions reflect more landscape-based approaches.

The technologies listed in **Table 1** are part of the "protection" strategy for coastal management defined in Wong et al. (2014) with the exception of the "managed retreat" which is one of the fundamental three principles of coastal zone management, and "elevated buildings" which is commonly listed as part of an accommodation strategy (section 1.5). The artificial elevated dwellings mounds, the so-called terps, are included under the category "soft solutions" as they reflect a landscape-based approach. Elevated buildings are listed as a hard solution because they utilize structural engineering.

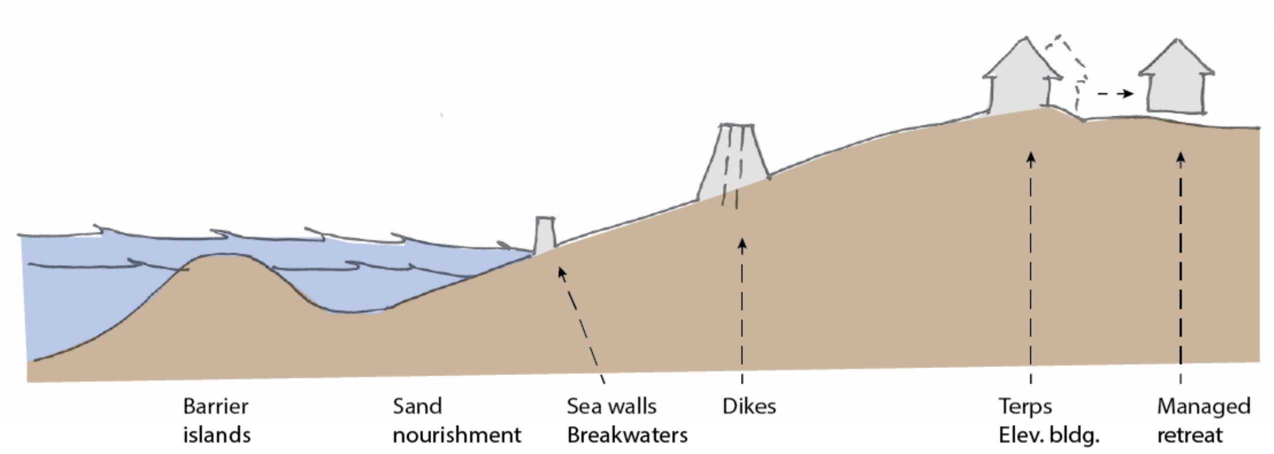


***Fig. 3.*** *A sketch of different protection technologies. Sketch by Eva Sara Rasmussen.*

## 2.2. Findings in a Danish context

The review of the state of the art of Danish coastal protection technologies has investigated 33 interventions historically and recently implemented over a time span of 5 centuries, ranging from the year 1500 to the year 2017 (**Fig. 4**; **Table 2**).

The analysis showed, that the occurrence of extreme storm surge events was the primary driver for the implementation of coastal protection in the different Danish regions (**Fig. 4**). Some examples can be found in **Fig. 5**.

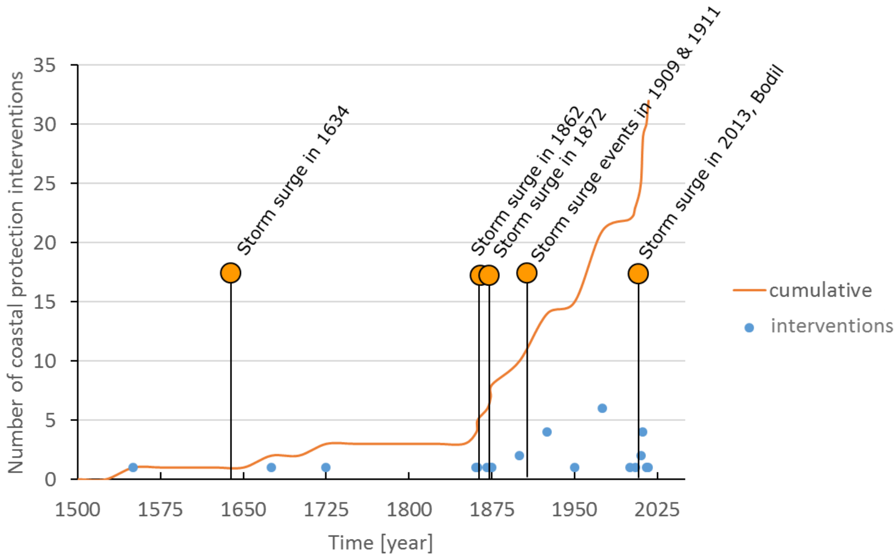


*Fig. 4. Coastal protection interventions in a Danish context implemented from the year 1500 up to current years along with the indications of extreme storm surge events (orange dots).*

12% of the coastal protection interventions (four out of the 32 reported protection interventions) were implemented between the **16th and 18th century** solely in the Jutland coastal areas. The system of dikes at the Wadden Sea was initiated in 1553 (Dike at Tønder Marsken) and continued until 1981. The Wadden Sea was indeed characterised by very strong and intense storm surge events. One of the worst events occurred during the 11-12 October 1634, which followed the construction of the dikes at Gammel Frederikskog (1692) and Rudbøl Kog (1715) in the Southwest Jutland coast (**Table 2**). In the marsh areas, usually not protected by dikes, protection was made possible through artificial elevations of the terrain, the so-called terps (**Fig. 5**). In Denmark, about 60 examples of terps can be found, especially in the Southern coasts of the Jutland peninsula. The earliest terps were originally constructed around the year 1000 A.D., the oldest are dates in the early 13th century. The most recent terps were constructed in the 18th century (Grænseforeningen, 2018).

The 16th- to the 18th century was therefore characterised by the implementation of terps as a soft solution against high tides and storm surge and by the implementation of the first hard technical solutions, namely the dikes at the Wadden Sea in the south-west of Jutland.

Approximately 16% of the investigated coastal protection interventions occurred in the **19th century** (5 out of 32 interventions). In the 19th century, coastal protection interventions have developed also in Funen and Lolland Falster (2 out of the 5 protection interventions). The storm surge event in November 1872 hit the southern part of Denmark heavily causing an extreme increase of the sea level at Bornholm and all the Baltic coast from Copenhagen down to Lolland-Falster, in the Southern Funen islands and the south-eastern coast of Jutland. The lolandian dike (*Det Lollandske dige*) was built after this catastrophic event (1874-1877), which inundated the southern part of Lolland and Falster and the city of Køge. The need for coastal protection in the 19th century occurred probably also as a result of intensive land reclamation which arose in that period. According to Stenak (2005), 149 projects turned fjords, lakes and wetlands into farmland. The reclaimed land area corresponds to a total of 200,000 hectares, which is ca. 5% of the land area of Denmark (Danish Environmental Protection Agency, 2005).

In Gyldensteen Strand in the northwest coast of Funen, a process of land reclamation was initiated in 1871 following dikes construction. The remaining interventions during the 19th century were implemented in the Jutland coasts (3 interventions): the construction of hard technical installations in the Wadden Sea continued with the implementation of the Højer sluice and Højer dike (1861), which were built to protect Ny Frederikskog; coastal protection against erosion of the Jutland west coasts was implemented in 1870 through groynes; the same happened at Thyborøn in Northwest Jutland. The Thyborøn channel was formed as a result of a storm surge event in 1862 and in order to avoid coastal erosion and to maintain the status of the channel, the coasts were equipped with groynes implemented in the period 1875-1892.

The **19th century** was therefore characterised by the implementation of solutions which were predominantly hard-technical solutions (dikes, sluices – often linked with land reclamation), and had seen the implementation of protection against erosion in the shape of groynes and breakwaters.

Ten out of the 32 reported protection interventions were completed in the **20th century** (app. 30%), of which three occurred in the Copenhagen capital region, one in Funen, and six in Jutland. There have been no projects involving coastal protection of the capital city of Copenhagen until before the beginning of the 20th century (though it needs to be highlighted that much of the early urban expansion in Copenhagen occurred on former sea bed including e.g. Christianshavn built in the 17th century). Amager Strandpark was built in 1934 with the main function of beach park (AOK, 2008). Amager Strandpark is a combined solution which has a potential for coastal protection against storm surge in the South East part of Copenhagen (Rambøll, 2015); in 1943 the Kalvebod dike which protects Vestamager was finalised (Hansen, 2018; Miljø og Fødevareministeriet, 2018), and Køge Bugt Strandpark was built only after 1979. The storm surge event in 1872, which also affected Køge Bugt, was the heaviest event which has occurred in the areas around Copenhagen.

In the same century, the completion of the dikes at the Wadden Sea was carried out: the *Fremskudte* dike was built in 1981 in connection with the Vidå sluice construction. Ribe dike and Kammersluse were built in the period 1909-1912 after the storm surge event occurred between 1909 and 1911. The two sluices at Hvide Sande, *Gennemsejlingsslusen* and *Afvandingsslusen* were implemented in the period 1928-1931. The first had the function of regulating water level and salinity in the Ringkøbing fjord. The second sluice was also built for the purpose of improving navigation through the Ringkøbing Fjord rather than for storm surge protection. The sluices were central for the development of the town of Hvide Sande. In Funen, the reinforcement of the dikes at Gyldensteen Strand occurred in 1950.

The problem of coastal erosion on the West Coast of Jutland between Lodbjerg and Nymindegab was addressed through soft solutions in the form of sand nourishment in the second half of the 20th century.

***Main findings****: Historically, the implemented solutions involved predominantly hard-permanent technical solutions as dikes and sluices, soft solutions as coastal replenishment through sand nourishment, and systems of technologies combining both hard and soft solutions, as beach parks.*

**Recent interventions**

In the recent years (**from the year 2000**), the driver for the development of recent coastal protection technologies is primarily due to the effect of climate change inducing both sea level rise and an increase of extreme storm surges, rather than land reclamation for farming.

Our investigation has reported 13 recent coastal protection interventions of which 6 are located in Jutland, 5 in Zealand, and 2 in Funen (Table 2).

In the Jutland coastal cities, interventions involved the renovation of Nørresundby waterfront (higher quayside with recreational functions), which started in 2010: the increase of the 650 m long quay edge gave the opportunity to renew the former industrial area by making it attractive, greener, and more connected to the fjord. The final increase of the quay edge and the implementation of recreation and esthetical elements (e.g. wooden terraces, a 3.5 meter wider promenade) was finalised in 2015. This allows providing a recreational waterfront not only for the residents of the areas but also for any passing pedestrians, cyclists or whoever wants to spend their free time there, inviting them to spend time in the area.

Another multi-functional intervention is the concrete floodwall at Lemvig, which was built between 2012 and 2013 and serves as a barrier against storm surge and sea level rise. The seawall is a hard technical solution but also a multi-functional element: intersections allow passing traffic through the wall and stairways and benches hang on the wall for public use. The square tiles are decorated with mosaics of glass and ceramics created by children of the city. Additionally, the floor of the new buildings in Lemvig harbour areas was elevated in connection with the project.

In Aarhus in 2015, a combined sluice, pumping station, and dike was opened in proximity to the harbour. The project is a climate change adaptation project addressing increased heavy rainfalls and sea level rise and storm surge events due to climate change. The sluice protects from sea level rise, while the six pumps pump water from the river standing behind, into the ocean. Additionally, areas around the sluice, Havnegade, and Europaplads have been lifted. The three main technological elements protect up to a +2 meter water level and ensure that the city centre is protected also against heavy rainfalls (Miljø- og Fødevareministeriet / Miljøstyrelsen, 2015).

Fredericia C started a process of harbour renovation in 2015. The project has involved the construction of a flood wall built along the old harbour in combination with planted slopes. The solution creates a new recreational area along the waterfront, secures the access to the water, and protects against storm surge. The recreational area is constituted of open spaces and path areas (Dansk beton, 2018a).

The sluice and pumping station, constituted of four pumps, implemented in Vejle was opened in 2016. This project is another example of how to use hard solutions to create additional values (Dansk beton, 2018b). The project enables multi-functionality since it combines a climate project, sewage project, and urban space project into one. The new urban space around the pump and sluice facility is thought as a form of platform positioned on top of the facility and a floating bridge. The bridge is thought as a social

element where also canoes can moor. The platform is thought as a space where people can take a break from other activities (e.g. shopping).
In Funen, in 2013 some of the dikes at Gyldensteen Strand broke and this enabled the development of a restoration project. This was the first restoration project occurring in Denmark following the coastal management principle of managed retreat and re-alignment (see Section 1.5 and 2.1). Instead of reclaiming land, and building protection, the sea water is invited "back in again" to restore the original lagoon which existed before the process of land reclamation. To protect the town of Bogense, 3.5 kilometres new dikes of 3 meters height were built around the coastal lagoon. A more profound analysis of this case is provided in section 4.5.

Coastal erosion in the northern coast of Funen was addressed in the period 1999-2014 by using the same combination of technologies as in the Jutland west coast, namely sand nourishment (soft solution) and the installation of breakwaters along the coasts (hard solution).

In Zealand Island, important interventions were made in Frederiksværk with the construction of the sluice inaugurated in November 2017. The sluice is located where the Arresø Canal meets Roskilde Fjord.

Recently, other types of temporary technologies have been emerging. In case of emergency, recent interventions involve the use of mobile barriers in the form of water and sand tubes. At Roskilde, these solutions were used in 2016. A water tube is a non-permanent solution, which is used temporarily only to withstand the event, but which does not provide any lasting extra values for the city.

***Main findings:*** *The recent coastal technologies which have been implemented in the last 18 years, from the year 2000 to the year 2017, have seen the use of hard solutions (dikes, seawalls, sluices) against storm surge and sea level rise, while sand nourishment, wave breakers and groynes were found to be the predominant solution against coastal erosions. The difference with the historical protection interventions is related to the tendency of using these technologies by enabling multi-functionality: e.g. by combining protection, recreation, and improved connections from the coasts/harbour to the city. Allowing multi-functionality is linked also to improving urban landscape, recreation, and aesthetic values.*


***Fig. 5.*** *Some examples of CPT in a Danish context. 5.a.: Terps (13th-18th century, source of picture: Vadehavets Formidlerforum (2012)); 5.b. Højer sluice (1861); 5.c. Amager Strandpark (1934 and 2005. Note: Amager Strandpark has potential as CPT); 5.d. The Fremskudte dike (1981); 5.e. Ribe sluice (1909-1912); 5.f. Sluice and pump station in Vejle (2016); 5.g & 5.h. Flood wall at Lemvig (2013) and its recreational elements. (see Appendix A for more details)*

***Table 2.*** *Review of Coastal Protection Technologies in a Danish context. Abbreviations: SLR: sea level rise; SS: storm surge; CE: coastal erosion; H: historical protection intervention implemented before the year 2000, predominantly between 1500 and 2000; R: recent protection intervention implemented after the year 2000. Further description can be found in Appendix A.*

| # | Project | Problem type | Hard | Soft | Combination | Non-structural | Region | Implementation | Type |
|---|---|---|---|---|---|---|---|---|---|
| 1 | *Sønderjyske værfter* (terps) | SS/high tide | | x | | | Southwest Jutland | $13^{th}$-$18^{th}$ century | H |
| **Dikes and sluices at Wadden sea** | | | | | | | **Southwest Jutland** | **1553-1981** | |
| 2 | -Dike at *Tønder Marsken* | SS | x | | | | Southwest Jutland | 1553-1556 | H |
| 3 | -Dike at *Gammel Frederikskog* | SS | x | | | | Southwest Jutland | 1692 | H |
| 4 | -Dike at *Rudbøl Kog* | SS | x | | | | Southwest Jutland | 1715 | H |
| 5 | -*Højer* sluse and Højer dike | SS | x | | | | Southwest Jutland | 1861 | H |
| 6 | -The *Fremskudte* Dike and *Vidå* sluice | SS | x | | | | Southwest Jutland | 1981 | H |
| **Coastal protection at *Thyborøn*** | | **SS/CE** | | | | | **Northwest Jutland** | **1862-1978** | |
| 7 | -Groynes | CE | x | | | | Northwest Jutland | 1875-1892 | H |
| 8 | -Sand nourishment | CE | | x | | | Northwest Jutland | 1970 | H |
| 9 | -Sand dike | SS | x | | | | Northwest Jutland | 1974-78 | H |
| 10 | The lolandian dike (*Det lollandske dige*) | SS | x | | | | Lolland | 1874-1877 | H |
| 11 | *Ribe* dike and *Kammersluse* | SS/ navigation | x | | | | Southwest Jutland | 1909-1912 | H |
| 12 | *Hvide Sande* sluice: *Afvandings- and Gennemsejlingssluse* | Regulating water level/ navigation | x | x | | | Jutland West coast | 1928-1931 | H |
| 13 | Protection of Jutland west coast: groynes/breakwaters | CE | x | | | | Jutland West coast | 1870 | H |
| 14 | Protection of Jutland west coast: sand nourishment | CE | | x | | | Jutland West coast | From 1990 | H |
| 15 | *Amager* Beach park | Recreation* | | | x | | Zealand East coast | 1934, 2005 | H |
| 16 | *Vestamager* dike (Copenhagen) | SS | x | | | | Zealand East coast | 1943 | H |
| 17 | *Køge Bugt* Beach park | SS | | | x | | Zealand East coast | 1976-1979 | H |
| **Protection at Gyldensteen Strand** | | | | | | | **Northwest Funen** | **1871-2013** | |
| 18 | Dikes at Gyldensteen Strand | Land reclamation | x | | | | Northwest Funen | From 1871 | H |
| 19 | Gyldensteen Strand: dikes' reinforcement | SS | x | | | | Northwest Funen | 1950 | H |
| 20 | Gyldensteen Strand: restoration project | SS | | | | x | Northwest Funen | 2013 | R |
| 21 | Floodwall at Lemvig | SS/SLR | x | | | | North Jutland fjord | 2012-2013 | R |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 22 | Nørresundby Waterfront (Aalborg) | SS/SLR | **x** | | | | North Jutland fjord | 2010-2015 | R |
| 23 | Sluice, dike, and pumping facility in Aarhus | SS/SLR | **x** | | | | Jutland East coast | 2015 | R |
| 24 | Combined sluice and pump station in Vejle | SS/SLR | **x** | | | | Jutland East coast | 2014-2016 | R |
| 25 | Harbour renovation at Fredericia C | SS/SLR | **x** | | | | Jutland East coast | 2015 | R |
| 26 | Sluice in Frederiksværk | SS/SLR | **x** | | | | Zealand fjord | 2017 | R |
| 27 | Reinforcement of Vestamager dike | SS/SLR | **x** | | | | Zealand East coast | 2012 | R |
| 28 | Addition of a sand island to Amager beach park | SS | | **x** | | | Zealand East coast | 2005 | R |
| 29 | Elevated levels floor buildings (Lemvig harbour)* | SS/SLR | **x** | | | | North Jutland fjord | 2013 | R |
| 30 | Coastal protection of North Funen: sand nourishment and wave breakers | CE | **x** | **x** | | | Funen | 1999-2014 | R |
| 31 | Floodwall at Gentofte | SS/CE | **x** | | | | Zealand East coast | 2014-15 | R |
| 32 | Mobile flood protection barrier in Roskilde | SS | | | | **x** | Zealand fjord | 2016 | R |

*main function: beach park with a potential for coastal protection; **implemented along with the wall;

## Danish pipeline projects

Denmark and the Danes need to be prepared and to adapt to future climate change. In order to tackle the climate change effects, which might change the status of our coasts and threaten coastal cities, several municipalities have started to plan solutions for protecting the coasts from erosion and the built environment from coastal floods. As an example, in the Zealand, the project "*Nordkystens Fremtid*" will act on the 58 km long north coast of Zealand, mostly through slope protection and sand nourishment, in order to decrease coastal erosion (see section 4.3).

Despite the implementation of the pumping station and the sluice (see section 2.2.), Vejle needs to secure the city from coastal floods rising from the fjord. Therefore, the city of Vejle has been working on three scenarios for storm surge protection. The central element is a traditional dike which gives in the different scenarios, the opportunity of being combined with other systems: harbour activities, recreation, and transportation. For more details, see section 4.4.

The city of Copenhagen is also planning to implement coastal protection in the form of dikes and sluices to protect the city from the north and from the south, which has resulted into the municipal storm surge plan (Københavns Kommune, 2017).

Roskilde recently completed a flood wall by the marina to protect assets from storm surges. The wall is partly a permanent structure, partly comprising temporary mobile installations.

In Funen, the city of Odense is planning to implement several installations combining sluices, flood walls and dikes. Assens, another city in Funen, has also been working on flood protection at the harbour areas: also in this case, the main technologies involve flood walls, dikes, and sluice gate combined through multifunctional principles.

Additionally, a number of projects, which are distributed almost homogeneously all over Denmark, will involve installations of sluices and gates (Henriques, 2017): Frederikssund, Køge, Korsør, Salskøbing, and Randers are at a conceptual design, the planning of the sluices at Esbjerg and Thyborøn is under preparation while consultations are ongoing for Kerteminde, Final construction of the sluice for the city of Kolding is expected in 2019. The practical implementation of these coastal protections, in several cases, sees a number of challenges: the political will, the financial support, the subdivisions of the financial costs between the involved stakeholders (land/property owners; municipality, utilities) are some of the limiting factors.

Facing the challenge: how to use the historical hard mono-functional solutions to create added values for the coasts and for the cities, to preserve culture, and natural values? Could the financially-related aspects be faced through the provisions of added value which might be the key used to tackle the financial problems?

***Main findings****: the driver for implementing new pipeline projects is sea level rise and storm surge events. Dominant new technologies are historically used hard technologies such as dikes and sluices; a combination of nourishment and slope protection against coastal erosion.*

## 2.3. Findings in an international context

The review of the coastal protection in an international context has involved 19 examples coming from the Netherlands, Germany, Austria, France, England, Russia, Japan and the United States (**Table 3**).

The most massive coastal technologies which were historically built in an international context were certainly the systems of dams and gates implemented in the southwest of the Netherlands from 1950 under the Delta works project (1954-1997) to protect against storm surge from the North Sea. The project includes 13 sub-projects involving hard designed technical solutions, i.e. systems of levees, dikes, gates, and storm surge barriers. The project helped against storm surge events from the North Sea. In our analysis, two out of the 13 sub-projects were reported. Worth to mention is the *Maeslantkering* storm surge gate that was completed in 1997 and which protects the city of Rotterdam (**Fig. 6**). The peculiarity of this technology stands in the two horizontal rotating gates, which are located in their dock in the open state. The *Oosterschelde* barriers is another sub-project in the Delta Works which was opened in 1986. The project is one of the main constructions in the Delta works and it closes *Oesterscheld* estuary from the North Sea.

The Thames barrier in London is one of the largest movable flood barriers in operation since 1984 and it protects 125 $km^2$ of central London. In Germany, a massive project is the Eider barrage which opened in 1973. It is 5 km long and incorporates 5 gates.

***Main findings:*** *also in the international context, historically there has been an (over)exploitation of hard measures driven by the intention of protecting against flood caused by storm surge.*

Recent relevant examples from the Netherlands are: at *Katwijk* with a project where parking is integrated with flood protection and recreation; Dakpark in Rotterdam consisting of a roof park integrated into a dike; in the city of the Hague it was introduced a series of interventions on the Boulevard Scheveningen involving a multifunctional seawall and beach nourishment (**Fig. 6**).

The Super Levee along the Arakawa River in Tokyo is another example of a multifunctional system. The super levee is completely integrated into the urban landscape and improves connections and access to the coast. The project was promoted in conjunction with an urban development project along the river. A huge risk for floods existed in the low-lying areas, which were required to be evacuated for the creation of uplands. The super levee projects have been completed at 13 sites and two sites are still in progress. Most of the dwellings were relocated behind the super levees, leaving the possibility for using the dikes for e.g. park (Nakamura et al. 2013).

Similarly to Maeslantkering and the Delta Works, the Saint Petersburg Flood prevention facility complex constituted 11 dams and locks and was finalised in 2011 to protect Saint Petersburg.

A structural solution, which might be implemented in connection with building's renovation refers to: elevating the foundation height of the building or adapting the buildings to floods by adopting gates which can close doors and openings in the masonry as in Hafen city in Hamburg. These solutions focus on protecting a single building rather than a larger area of settlements. These types of solutions constitute a relatively new concept in the panorama of coastal protection. However, many streets in Chicago were raised in the 1850s and the 1860s in order to implement sewers to combat diseases and provide urban drainage (The Encyclopedia of Chicago, 2005). Along with this intervention, many buildings were raised and some relocated to other areas. It was reported that this intervention has doubled the value of some of the raised buildings.

***Main findings:*** *As in the Danish context, recent coastal protection interventions in an international context tended to have more attention towards the combination of different functions and the creation of added values to the local urban community.*

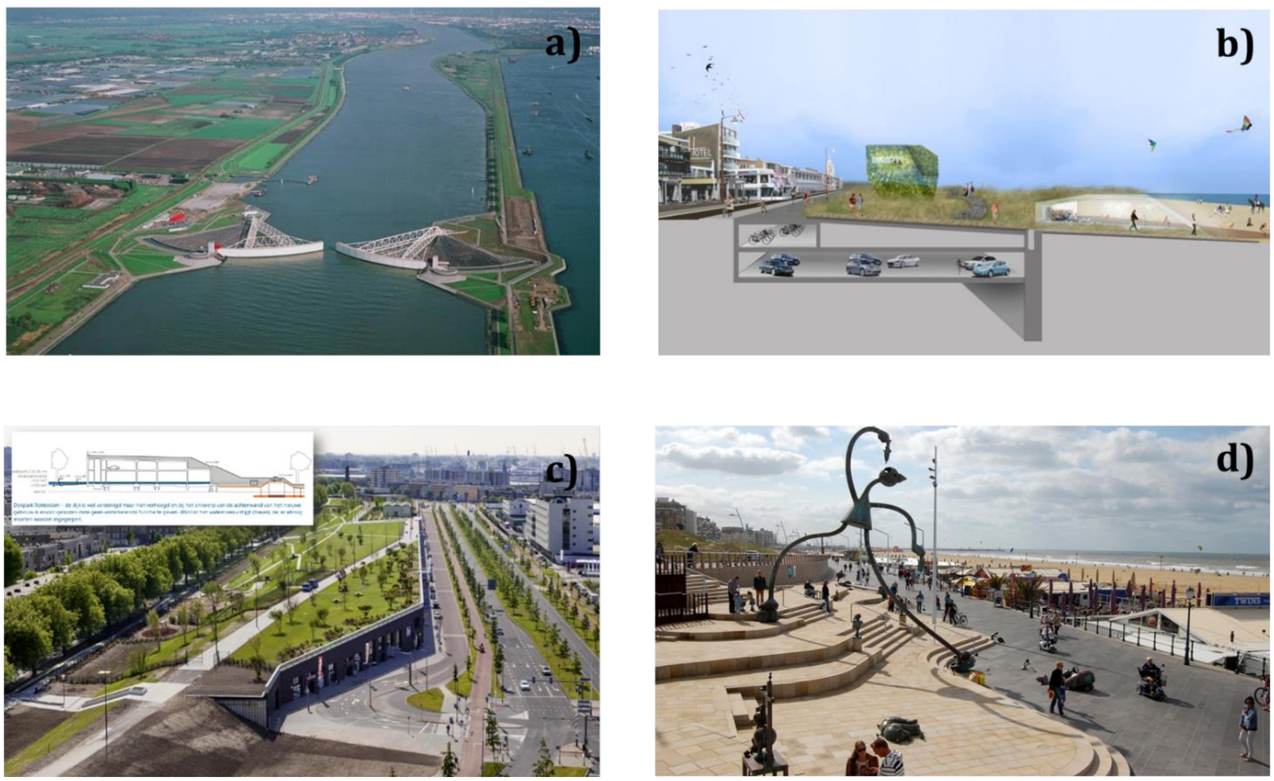


***Fig. 6.*** *Examples of coastal protection in the Netherlands. 6.a. Storm surge barrier Maeslantkering, as a historical solution, part of the Delta works. 6.b. Integrated dunes and parking at Katwijk; 6.c. Dakpark: integrated roof-top park and dike at Rotterdam; 6.d. Integrated flood walls, sand nourishment, and dikes at Scheveningen.*

***Table 3.*** *Review of Coastal Protection Technologies in an international context. Abbreviations: SLR: sea level rise; SS: storm surge; CE: coastal erosion; H: historical protection intervention implemented before the year 2000, predominantly between 1500 and 2000; R: recent protection intervention implemented after the year 2000. Further information can be seen in Appendix B.*

| | **Project** | **Problem type** | **Hard** | **Soft** | **Combination** | **Non-structural** | **Country** | **Implementation** | **Type** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Thames barrier | SS | x | | | | England | 1984 | H |
| 2 | Eider Barrage | SS | x | | | | Germany | 1973 | H |
| 3 | Hondsbossche en Pettemer Zeewering | SS | x | | x | | Netherlands | 1880/2014 | H |
| 4 | Afsluitdijk | SS | x | | | | Netherlands | 1927-1932 | H |
| 5 | Oosterschelde barriers (Delta works) | SS | x | | | | Netherlands | 1986 | H |
| 6 | Maeslantkering storm surge gate | SS | x | | | | Netherlands | 1997 | H |
| 7 | Super levee in Tokyo | SS | x | | | | Japan | 2012 (ongoing) | R |
| 8 | Saint Petersburg Flood Prevention Facility Complex | SS | x | | | | Russia | 2011 | R |
| 9 | Inner Harbor Navigation Canal Lake Borgne Surge Barrier | SS | x | | | | USA (New Orleans) | 2013 | R |
| 10 | Katwijk, Holland | SS | | | x | | Netherlands | 2013-2015 | R |
| 11 | Dakpark, Rotterdam | SS | | | x | | Netherlands | 2013 | R |
| 12 | Boulevard Scheveningen, The Hauge | SS/SLR | | | x | | Netherlands | 2011 | R |
| 13 | Cleveleys | SS | x | | | | England | 2008 | R |
| 14 | Mobile barrier, Stein-Krems | SS - river | | | | x | Austria | 2013 | R |
| 15 | Mobile barrier, Grein | SS - river | | | | x | Austria | 2010 | R |
| 16 | Water tubes, Mont de Marsan | SS - river | | | | x | France | 2014 | R |
| 17 | Managed retreat, Alkborough Flats | SS/SLR | | | | x | UK | 1999-2006 | R |
| 18 | Managed retreat, Noordward | SS/SLR | | | | x | Netherlands | 2016 | R |
| 19 | Elevated buildings, HafenCity Hamburg | SS/SLR | x | | | | Germany | 2001-2009 | R |

## International pipeline projects

Some examples of future coastal protection interventions which will be implemented in the international context are also provided along with this study.

Coastal protection projects against flood have been planned in Italy, Thailand and the United States.

- It is worth to mention the project “MOSE” in Italy, which will involve 78 gates protecting the coastal lagoon of Venice from the high tides from the Adriatic sea.
- In NYC-Manhattan (USA), a future project will involve a dike as a main multi-functional element: A park is going to be located on top of the dike and a tunnel will be located into the dike core.
- Another pipeline project is the Dryline in New York which is a going to be a 12km infrastructural barrier incorporating public spaces and surge barriers.
- Finally, although particularly relevant in case of heavy rainfalls, the city of Bangkok in Thailand is planning a system of underground tunnels, which may have the potential of generating hydropower.

Two recent projects developed as proposals for design completions in coastal areas subjected to coastal inundation indicate an emerging transition from protection measures to a strategy that leans more towards an accommodation and managed retreat approach.

A proposal for Galveston Island State Park (entitled Sand + Storm + Sea + Strand) won the American Society of Landscape Architects’ Professional Award of Excellence 2017. The design suggests to (re-)introduce a dynamically changing coastal ecosystem with migrating sand dunes, expanding salt marshes, rich in biodiversity and a centre for recreation and learning for visitors (ASLA, 2017).

On Long Island, the widely published draft development plan (entitled Bight: Coastal Urbanism) suggests a managed retreat from the coastline. Over the coming 50 years, settlements in flood-prone areas are gradually phased out and compensated by new densified settlements on high ground and a realigned coastal landscape and buffer zone protecting the city against storm surges and extreme storm events (MIT Architecture, 2017).

## 3. Perspectives on the holistic coastal protection and organization

This chapter aims to develop an integrated framework to help assessing and working with coastal protection in Denmark. The framework encompasses varying social, technical, economic and spatial dynamics reflecting the particular project site context.

### 3.1. Cultural background for the cultivation of the coast

Since the publication of the Nordic action plan "*Kulturmiljøet i landskabet*" in 1996 (with the Secretariat of the Danish Forest and Nature Agency, Denmark), the Nordic cultural environment cooperation has focused on the historical coastal culture in the Nordic region as an area that requires special attention due to drastic changes which have occurred in recent decades.

In 2001, the European Union issued a recommendation to the Member States to implement the Integrated Coastal Zone Management Principles (ICZM) in national law. As a consequence, the Nordic Council of Ministers' Nature, Outdoor and Cultural Environment Group initiated the report "Historical Coastal Culture - A Resource in the Coastal Landscape" (Danish title: *"Historisk kystkultur – En ressource i kystlandskabet"*), published in 2004. The publication has concluded that the coastal scenery depicts in many cases, the most attractive areas in the Nordic region. The attractiveness of the coastal scenery is based on the experience in working with coastal landscape, which lays the foundation for the expression of the natural and the cultural environment of a place. The cultural environment contains a story of human adaptation to the natural surroundings and phenomena. Working with the different coastal landscapes has shown that the natural habitats, which have been particularly attractive to humans, have almost always been influenced and shaped by human resource utilization. It is deeply rooted in our Nordic heritage that coastal cities are founded and developed in the respectful interaction with the basic conditions of nature – in a balance between human needs and the fundamental dynamics of nature.

Climate change, which induces sea level rise and more intense and frequent storm surges, has already posed a new risk for the natural surroundings and coastal populations. Based on the Nordic coastal tradition, it is therefore natural, that we need to tackle these phenomena by working with combined efforts and solutions: Securing the coasts by coupling solid technical solutions, and providing accurate assessment of the image and attractiveness of the coastal landscape, while working with a fundamental respect for the Nordic coastal culture, cultural history and coastal life.

With the confrontation with climate change, there is a need for innovation of this cultivation of the interaction between human and nature - between socioeconomics and coastal dynamics. This is aligned with Wong and colleagues, who in their comprehensive international review for the IPCC on coastal systems conclude that "few studies consider (coastal) adaptation and those that do generally ignore the wider range of adaptation measures beyond hard protection options. Integrated studies considering the interactions between a wide range of RSLR (relative sea-level rise) impacts as well as trade-offs between diverse adaptation options are missing." (Wong et al, 2014, pp. 382-383).

## 3.2. Role of the coasts and the coastal cities

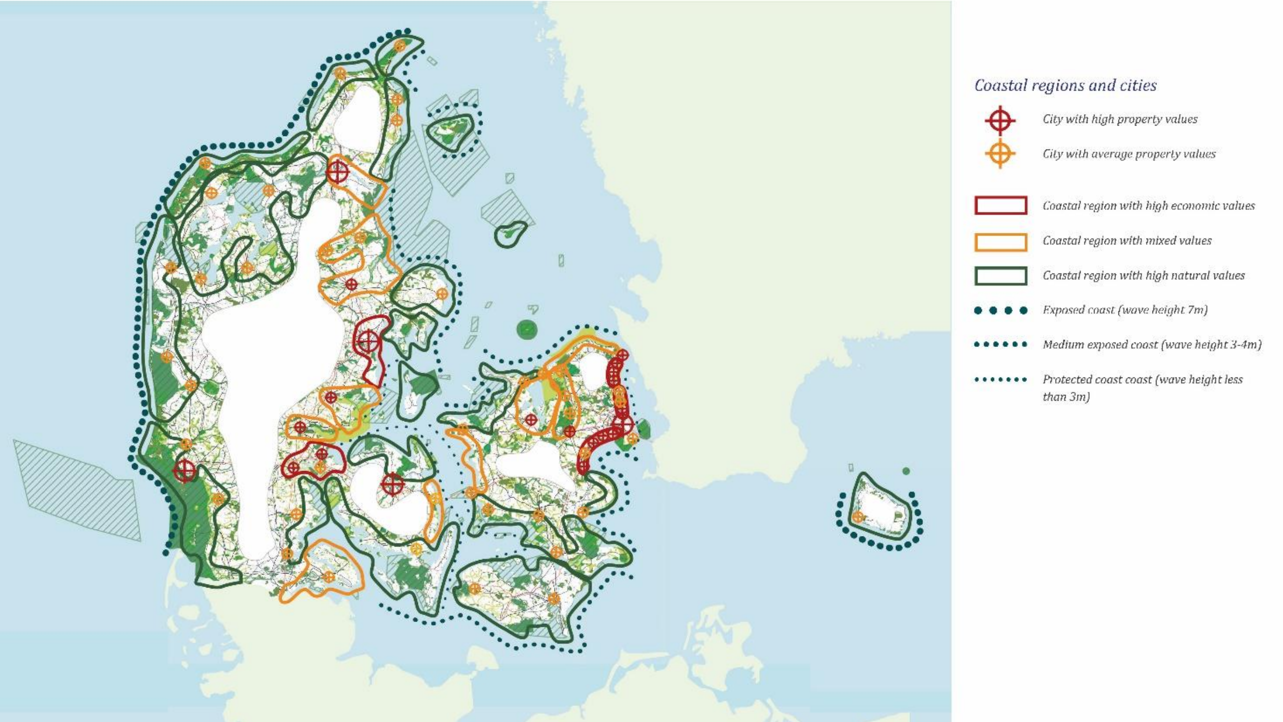


***Fig. 7.*** *Map of biodiversity, coastal protection, wave exposure and property values. The coastal towns and villages are marked with colours from red (highest property values) to orange (average property values) and green (lowest property values). Map based on data from the Data Protection and Efficiency Board, NST in the form of digital portal at http://miljoegis.mim.dk/spatialmap?&profile=miljoegisklimatilpasningsplaner. Tidal water statistics, published by the Danish Coastal Authority, 2017: http://www.masterpiece.dk/UploadetFiles/10852/36/Højvandsstatistikker_2017_web.pdf and the erosion atlas: "Bølgeklima for 40 lokaliteter i danske farvande med vurdering af klimaeffekter for udvalgte lokaliteter", prepared by DHI for Danish Coastal Authority in 2012. Map by Eva Sara Rasmussen.*

The majority of urban communities in Denmark are located in the proximity of the coasts. The coasts and their cities serve as unifying places in the landscape for human activities. In addition, in coastal cities, business activities and high property values are central elements. The landscape attractiveness of the coastal cities and their economy have been culturally and historically founded on the duality between the built environment and the free natural forces.

By combining publicly available information about biodiversity, existing coastal protection, property values and the coastal dynamics, it is possible to identify, on the one hand, the most economically strong urban communities, and on the other hand a number of cohesive coastal regions in Denmark (**Fig. 7**).

The map (Fig. 7) shows the coastal areas with high natural and economic values (depicted with a green outline and a red outline respectively) and the areas characterised by mixed values, i.e. both natural and economic values (shown with an orange outline). The map shows additionally the coastal cities with high and average property values (depicted as red and orange pins respectively).

Additionally, the mapping (Fig. 7) can also be used to highlight dissimilarities and common features across the country's towns and villages in relation to how they manage and develop coastal protection and how they collaborate across administrative boundaries. This allows also to identify when combined efforts are needed in order to preserve both the economic and the natural attractiveness of the place.

The quantitative analysis of technical coastal protection, economic values and natural resources (wave energy and biodiversity) is expected to be a good basis for implementing a holistic thinking which involves: developing the Danish tradition for beautiful coasts and projects with a high innovative power in line with the historical traits of a Nordic coastal culture.

### 3.3. The relation between economy, organization and technical development

The mapping of property values and biodiversity (Fig. 7) highlights interesting aspects of the economy, organization, and technical development of coastal protection strategies. The map points at how the different sizes of the local economy can be a "driver" for developing different types of project, and organizational forms to work with climate change adaptation of the Danish coastal areas.

The decisive parameter appears to be the correlation between three different dimensions: 1) Technical scale and complexity of climate challenge compared to 2) local property values and 3) the local balance between private and public land ownership.

Working with climate adaptation of coasts in Denmark for more than 20 years, the authors of this report have observed the following situations:

1. Coasts dominated by a high level of private ownership combined with high property values and small technical complexity have reflected in many small coastal protection projects along short stretches of the coasts. *Example: The coast of Oresund.*
2. Coasts with a mix of public and private ownership and relatively high property values, natural values and medium complexity seem to lead to both single projects in municipalities, smaller private projects and regional projects involving a larger portion of the coastal territory. *Examples: Lemvig Harbor, Vejle Municipality, Køge Municipality and Zealand's north coast.*
3. Coasts blending public and private ownership and relatively low property values seem to lead to few or no realized projects, regardless of the level of technical complexity. *Example: Lolland Municipality and the Northwest coast of Jutland.*

Three approaches to coastal protection can be realistically "matched" to the three different types of situations reported above:

- Construction Project
- Development project
- Planning Project

<u>The construction project</u> is the "normal/traditional" approach for solving technical problems and requires a high degree of "familiarity" with the technical problem to address and how to solve solution scenarios. It is usually implemented when it is established that the project will be implemented. The construction project can be assigned to represents situation 1. *Example: Bellevue Beach Park.*

<u>The development project</u> is more abstract than the construction project. It phases a more technical complexity, combined with organizational and economic challenges. However, there is the willingness of the interested stakeholders for implementing the project. This type of project can be assigned to situation 2. *Example: Zealand's north coast and Køge Municipality.*

<u>Planning projects</u> are often initiated in regions with a weak economy, which weakens the means to take concrete action in the short term. It thus becomes crucial to try to counteract the worst consequences

of planning out of the problems e.g. by public communication on the situation and perspectives. *Example: Northwest coast of Jutland.*

On a socioeconomic point of view, it is also quite different whether it is the single stakeholder (e.g. the private landowner) or the wider society (e.g. municipality, state) who are driving the process of implementing coastal protection measures. Whilst the single stakeholder tends to produce projects which fit into situation 1, the public sector tends to develop projects which fit into situation 2. The public organisations have larger potential and finances for creating larger-scale projects which in return will lead to the protection of larger coastal stretches and added values for more people.

Former investigations and reports (e.g. Rambøll, 2015) on coastal protection has mainly described the challenges regarding financing and construction of the protection measures, with few investigations of a holistic approach to both landscape, process, cultural heritage and economy on the specific site, coastal city or coastal region.

## 3.4. Working with holistic coastal protection goals

Climate change is a "game changer" for our societies and way of life. Working with climate change and coastal protection is a complex task. When confronted with major changes we humans are forced to review our normal habits and consider: what to restore, what to keep, what to get rid of and what to reinforce.

Regardless of the local, present economy and technical requirements, it is required to work closely in constant dialogue with the local goals for the coastal protection. Goals that rise above the technical requirements, and point to the extent to which coastal protection should strategically be considered in a context of renewal or preservation of the current qualities of the site.

These strategies could be categorized into two categories: "hard" and "soft", where the "hard" protection approach traditionally require few changes from current working methods and is rather easy to describe. Roughly speaking the "soft" approach instead, demands engagement of a broader range of professionals in an interdisciplinary setting, mainly because of the level of innovation needed for these solutions compared with the traditional Danish coastal protection approach emphasising hard structures. The two strategies work with two strategic coastal protection goals. The "traditional/hard" coastal protection strategy aims at: (1) Reconstruction and (2) Reinforcement. In contrast, the "soft" coastal protection strategy aims at: (1) Conservation/restoration and (2) Renewal/Retelling.

But why even consider working with "soft" coastal protection strategies if this demands a more interdisciplinary approach and a probably longer implementation process and higher financial demands?

The answer to that question is not an easy one. First of all traditional "hard" strategies are expensive capital expenditures (Miljø og Fødevareministeriet, 2016). From a holistic socioeconomic point of view, expensive investments must be expected to provide more comprehensive solutions. Regarding the expected scale and magnitude of climate change, solutions that go further than "just" providing technical solutions – and contribute with innovation and beauty, must be the long-term need-to-have coastal protection goal, in order to subscribe the coastal protection in a context of renewing and developing our cultural identity.

## 4. Analysis of four selected cases in Denmark

This chapter provides an analysis of four selected coastal development initiatives in Denmark with a view to holistic coastal management.

### 4.1. A multi-criteria framework for analysing coastal protection

In line with the implementation of a more holistic framework for the planning of coastal protection (see Chapter 3), the authors propose a multi-criteria framework for the analysis of coastal protection initiatives. The intention is to provide a broad range of holistic assessment parameters. The multi-criteria framework includes five assessment criteria (3 quantitative and 2 qualitative criteria). These criteria are reported in **Table 4**.

***Table 4.*** *Multi-criteria framework for the analysis and planning of coastal protection*

| Criteria | Description | Type |
|---|---|---|
| **Technical security** | Knowledge of the technology; number of protected buildings;<br>Safety factors;<br>Risk management | Quantitative |
| **Economic consideration** | Savings compared to traditional technical solutions;<br>More funding opportunities in connection with adaptation of urban development and infrastructure development;<br>Improved urban development opportunities. | Quantitative |
| **Environment/ Nature** | Gains for nature and the environment;<br>Cooling of the city;<br>$CO_2$ reduction | Quantitative |
| **Innovation potential** | Process;<br>Technology;<br>Combination of possibilities;<br>Driving power for citizen involvement;<br>Adaptation to coastal dynamics. | Qualitative |
| **Coastal landscape** | Adaptation to the surroundings;<br>Recreational potential, Cultural heritage;<br>Recreational value;<br>Better and more exciting green/blue urban paces. | Qualitative |

Four cases were selected for further the investigation (**Table 5**). Geographically, the cases represent different regions in Denmark (**Fig. 8**): Vejle in Jutland, Gyldensteen Strand in Funen, Køge Bugt Strandpark and Nordkystens Fremtid in Zealand. Two out of the four projects are already built, namely Køge Bugt Strandpark and Gyldensteen Strand, while Vejle and Nordkystens Fremtid are in a planning phase. Køge Bugt Strandpark and Vejle are analysed in order to evaluate the effect in a densely built-up environment, while Gyldensteen Strand and *Nordkystens Fremtid* are planned in a less dense rural environment.

***Table 5.*** *Relevant cases in relation to coastal protection technologies in Denmark.*

| | Urban | Rural |
|---|---|---|
| **Municipal level** | Vejle | Gyldensteen Strand |
| **Regional level** | Køge Bugt Strandpark | Nordkystens Fremtid |

The four projects reflect a selection of smaller local site scale projects (i.e. Gyldensteen and Vejle), as well as two larger initiatives at the regional scale (i.e. Køge Bugt and Nordkysten). The Køge Bugt Strandpark was designed by considering the natural coastal dynamics and the artificially constructed landscape along Køge Bugt is a relevant case that calls for a critical review. Vejle city is relevant since its urban water system is challenged by a combination of different types of extreme events, including storm surge and sea level rise. It is therefore interesting to assess how the city is preparing to face this challenge. Nordkysten is a new development project addressing coastal erosion across towns and municipalities of which it is interesting to analyse drivers and potentials. Finally, Gyldensteen Strand is the first managed retreat and ecological restoration project in Denmark and therefore unique and contrasting in its approach to coastal development.

Below the criteria are qualitatively applied to assess the four selected cases.

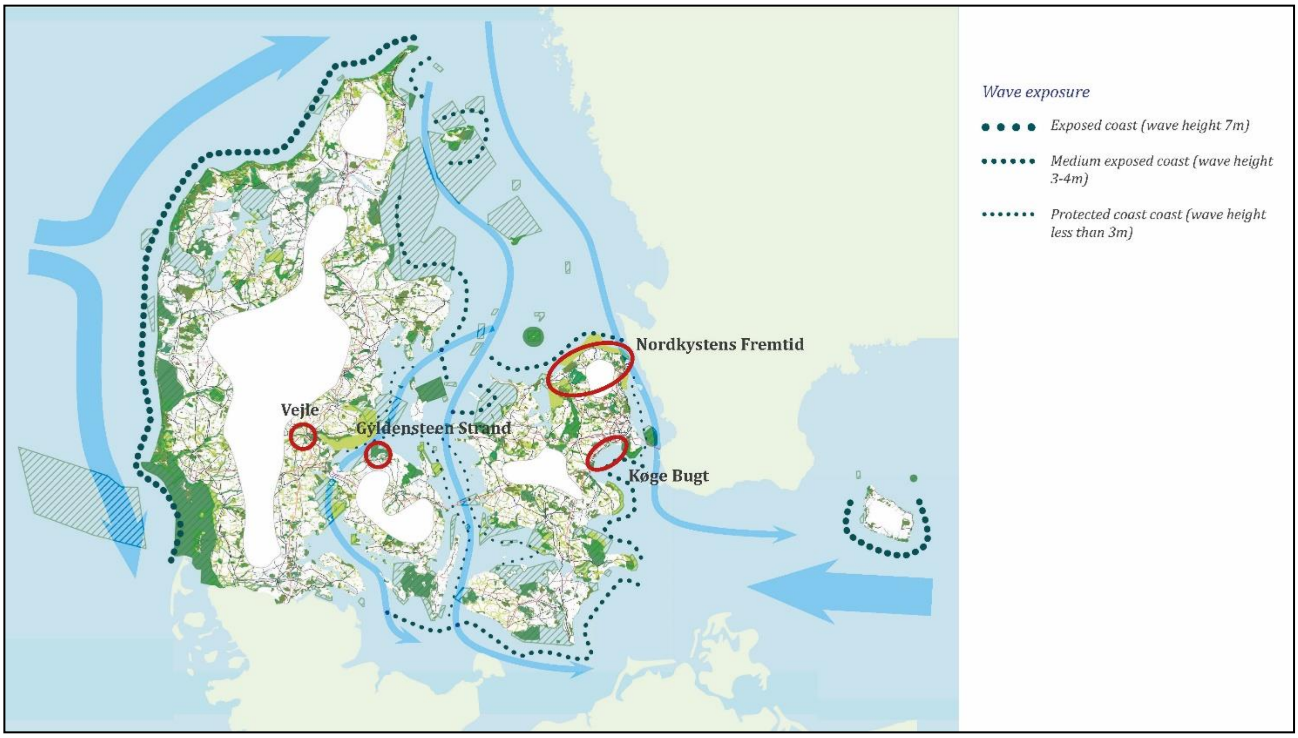


***Fig. 8**. Selection of cases on a map of wave forces and biodiversity. Map by Eva Sara Rasmussen.*

## 4.2. Køge Bugt Strandpark


**Description**

Køge Bugt is here defined as the coastline between Brøndby marina to the north and the southern port area of Køge to the south. The 30 km coastline is characterised by shallow waters and relatively low exposure to high energy wind and wave conditions from the open sea. The coastline is a curved bay area with a wide flat and low-lying hinterland and a number of streams discharge into the bay area (COWI, 2017). Historically the coastline is characterised by low-lying wetlands with wetland plants such as Phragmites along the shore. Further, the bay area is characterised by naturally formed barrier islands located off the coast and parallel to the coastline due to sand deposits transported from the sea and sedimented along the coast (Galathea 3, n.d.). The two peninsular sandbanks of Staunings Ø and Ølsemagle Revle located north of Køge are examples of this geologically significant and dynamically changing coastal landscape.

In 2011, the Danish Coastal Authority (DCA) identified Køge Bugt as one of 10 designated areas at risk of flooding in Denmark (please note that DCA defined Køge Bugt as the towns of Tårnby-Dragør, Ishøj, Solrød Strand og Køge). Storm surge levels for a 100-year event along Køge Bugt are expected to increase by approximately 50 cm (DMI, 2012) and 100 cm (COWI, 2017) by 2120 compared to the current level (note: these figures are adjusted for predicted sea level rise and land uplifting). A key issue is the flat hinterland which put larger urbanized areas at risk of inundated as a result of storm surges. According to a recent study, approximately 180.000 inhabitants in six municipalities along Køge Bugt are currently at risk of coastal flooding (COWI, 2017).

From the 1960s and onwards, the low-lying wetland area along the bay was developed into suburban residential housing estates as part of the southern extension of the Finger Plan towards Køge, predominantly led by the construction of the commuter train line to Køge which was initiated in the early 1970s and completed in 1983.

In the 1970s it was decided to develop an artificial island and lagoon system in the northern part of the bay between Avedøre and Greve. The purpose of the new land reclamation project was to increase the recreational destination value of the new southern urban growth corridor, to improve access to the sea and partly to protect the new settlements from coastal flooding. The resulting Køge Bugt Strandpark opened in 1980 and was designed with a 7 km coastline, two major barrier islands located between 300 m and 600 m off the natural coastline, six inland lakes, four marinas, up 45 m wide beaches and vegetated sand dunes (along with three groynes to retain sediments) (Fig, 4.2.). The artificial islands were constructed by using 5 million $m^3$ of sand, with 40% of the material being excavated from the local seabed at Køge Bugt (Galathea 3, n.d.).

The barrier island and sluice gate system along the streams and lakes in Køge Bugt Strandpark serve as a flood protection system and is designed to manage storm surges from the sea up to a level of approximately 3 meters above mean sea level (COWI/Hvidovre Kommune, 2015). The outer dikes in the dunes are designed with a clay core are designed mitigating the risk of storm surge impacts as well as reducing coastal erosion caused by waves. The sluice gates mitigate the risk of storm surges entering the three streams and catchments discharging into the lagoon, and hence they aim to reduce the risk of backwash flooding of inland settlements.
The outer dikes are supported by inland levees. As an example, the inner dikes in the municipality of Vallensbæk has a crest height of approximately +2,25 m DVR90 (Niras/Vallensbæk Kommune, 2014). The main road along the bay area, Gl. Køge Landevej, doubles as a de facto inland dike located approximately 300 meters from the coastline.

In 2017, the municipality of Køge provided a feasibility study of storm surge protection measures between Staunings Ø and the town centre. The planned crest height is +2,8 m DVR90. A key discussion point is whether to locate new dikes in the dunes of the natural dynamic barrier islands off the coast or, as an alternative, to implement new dikes inland on more static terrestrial land. Potential impacts on the protected habitats are critical factors influencing decision making. Further, the city has initiated an urban growth area in the former southern port area, Køge Kyst, which is designed with elevated building floor levels (+3,25 m), elevated seawalls and a potential new lagoon, meadow and beach landscape. The budget for coastal protection in the Køge Municipality is in the range of DKK 100 million (Niras/Køge Kommune, 2017). Annual operation and maintenance costs are in the range of DKK 1,2 million.


*Fig. 4.2. Map of Køge Bugt Strandpark (Source: http://onlinegrafik.dk/strandpark/soer.html).*

## Assessment according to the five chosen criteria

**Technical security**

The outer dike in Køge Bugt Strandpark has an existing crest height of approximately +3 m DVR90 which is roughly the equivalent of a 300-year storm surge event at present and a 100-year event in the year 2120 (COWI, 2017; DCA, 2011). The outer dike is integrated into the sand dunes and hardly visible. Further, the crest height can be elevated in the future without much effort, should the need arise.

The southern growth corridor of the Finger Plan is located in what has historically been a low-lying wetland area. This is reflected in the etymology though site names such as Kildebrønde ('spring wells'), Mosede ('bog'), Hundige ('ditch') and Greve (terrain 'depression') (Den Store Danske, n.d.; Navneforskning, n.d.). Frankly, this wetland area was first turned into a site for summer cottages and subsequently developed into a suburban housing area. As stated by a senior water professional in Greve some years ago, 'there is probably a reason why no Medieval market town has been located here' (Ingeniøren, 2008). A key national spokesperson on urban hydrology concurred that the town of Greve should never have been built at this location due to its exposure to flood hazards (ibid.).

As a result, the settlements along Køge Bugt are subjected to a range of interrelated challenges resulting from climate change. This includes sea level rise, higher storm surge levels, predicted more intensive cloudbursts, higher winter precipitation and shallower groundwater levels. Hence, the residential, industrial and commercial developments along the southern growth corridor of the Finger Plan are exposed to water challenges from above and below, from the sea to the East and from the river catchments to the West.

**Economic considerations**

The general partnership Køge Bugt Strandpark I/S was established in 1975 as a consortium covering two regional governments and seven local governments along the bay. Construction costs were supported by funding at the national government. Operation costs were divided between the regional governments (45%), the cities of Copenhagen and Frederiksberg (32%) and the municipalities of Hvidovre, Brøndby, Vallensbæk, Ishøj and Greve. Since 2008 operation costs have been covered by the latter four municipalities which have direct frontage to the beach park. The annual operation cost of Køge Bugt Strandpark is currently in the range of DKK 10 million. Maintenance costs have recurrently emerged as a critical issue for the proper management of the beach park (Westh, 2018). Additional funding for larger renovation projects is provided by the national government on an ad hoc basis (Strandparken, n.d.).

The natural meadows, mudflats and wetlands along the coastline of Køge Bugt have a protective effect on storms as they contribute to reducing the energy in waves and provide shelter. During extreme weather events, the natural buffer zone will contribute to lower flood levels on the land side and local higher storm surge levels on the seaside (DCA, 2011:78). A recent study published in *Nature Scientific Reports* estimates that wetlands in North-eastern USA reduced direct flood impact costs during Hurricane Sandy by DKK 3,7 billion (Narayan et al 2017). This might be also relevant for the wetlands along the coastline of Køge Bugt which might reduce the damage costs due to more intense storm surges in the low-lying areas around Køge Bugt.

**Environment/Nature**

The sandbanks and lagoon environment at Ølsemagle Revle and Staunings Ø is a wildlife habitat protected by Natura 2000. Further, the coastal landscape is considered a significant geological site of national interest (Niras/Køge Kommune, 2017).

The Køge Bugt Strandpark provides a wide range of habitats including secluded 'bird islands', lakes, sand dunes, coastal meadows, grasslands, forests and the open sea. Consequently, the beach park accommodates a diverse group of flora and fauna species.

During the construction of Køge Bugt Strandpark, more than 2 million plants of European Beachgrass (*Ammophila arenaria)* were transferred from the West Coast of Denmark to this new site with a view to stabilising the sand dunes and protecting the dunes from wind erosion (along with other salt-tolerant grasses, and some 200,000 trees and shrubs). The planting strategy is considered successful, though the provision of fertilisers in the first years have led to a wider expansion of these grasses which has implied higher maintenance needs than initially planned for.

The shallow waters of Køge Bugt, the bay area's relative protection from heavy winds, and a nutrient-rich marine environment lead to high seaweed growth rates which again leads to continuous deposits of seaweed on beaches along Køge Bugt. The decomposition of seaweed leads to smell problems and, according to many residents, the presence of dry seaweed reduces the aesthetic attractiveness of the beach environment. As a result, municipalities along the bay have decided to spend money on the regular removal of seaweed from the shoreline. Greve Municipality, as an example, spends DKK 2 million per year on the removal of a total of 8400 tonnes of dry seaweed from the municipality's 8,5 km coastline (Skjerning, 2017). That is one metric ton of seaweed per linear meter of coastline at a cost of 50 DKK for each ratepayer in the municipality every year.

**Innovation potential**

The artificial beach park Køge Bugt Strandpark has created a recreational spot for swimming, sailing, angling, walking and running in close proximity to around 1.2 million urban dwellers along the Roskilde and Køge growth corridors of the Copenhagen Finger Plan. The population in the immediate vicinity of the coast is approximately 400.000.

**Coastal landscape**

The natural environment and the dynamic coastal processes of the sandbanks at Køge Bugt were used as a precedent for the development of the artificial barrier islands along the northern coastline. The fact that the design of Køge Bugt Strandpark was inspired by and based on the natural coastal morphology of the Køge Bugt bay area is considered a key strength of the project (Galathea 3, n.d.).

The beach park provides wide sandy beaches as a new contribution to the natural coastal environment of Køge Bugt dominated by wetlands and meadows. The thoroughly designed beach environment has developed into a regional destination site for bathing and attracts approximately 1 million visitors per year (Buus, n.d.).

**Key insights from Køge Bugt Strandpark**

The Køge Bugt Strandpark project shows how offshore coastal protection can be well integrated with the development of new recreational landscapes that serve multiple functions. Further, Køge Bugt

Strandpark exemplifies how natural processes can be utilised to develop a new beach which meets the design objectives. The project is flexible in the sense of being easily adaptable to higher flood protection levels without significant changes to the landscape. Still, allocating funds to cover ongoing maintenance costs is of pivotal importance for the long-term operation and success of the coastal flood protection system exemplified by the beach park.

Risk reflects the accumulated effects of the levels of exposure, hazards and vulnerability (Cardona et al., 2012). Lessons learnt from Greve highlights the importance of mitigating flood risks through appropriate planning, i.e. by avoiding new developments in areas that are highly exposed to flood hazards such as historical low-lying coastal wetlands. The development of *Køge Kyst* on post-industrial port areas is symptomatic for urban transformation processes in Denmark and at risk of putting more properties, assets and people at risk of coastal inundation.  Despite the efforts to install storm surge protection measures including dikes and elevated ground floors, it is up for discussion if the new developments on the harbour front risk being short-sighted solutions and a poor investment long term.

## 4.3. Nordkystens Fremtid


**Description**

Zealand's north coast includes the approximately 58 km long coastline from Hundested in the west to Elsinore in the east on the north coast of Zealand. Geologically, the north coast is very complex with both soft and sandy as well as hard stretches with more durable sediments. The largest and oldest towns along the north coast are commonly located on sites with relatively hard sediments of for example moraine clay.

In the 16th century, coastal erosion became a major problem on the north coast. It was solved in the first half of the 18th century by laying out seaweeds on the most exposed areas. By the end of the 18th-century, certain coast stretches were planted with forest, which minimizes erosion and creates a more stable coastline.

Until the mid-1900s, the coast remained sparsely developed, with only a few historical settlements in e.g. Hornbæk, Gilleleje and Elsinore. From the mid-20th century, there was a rather strong development of summer cottage areas along the coast, which led to the growth of previously small fishing villages, such as Hundested, Tisvildeleje, Liseleje and Rågeleje. The newer settlements of summer houses along the coast was predominantly established, on poor farmland, and lured on the coastlines natural and cultural-historical recreational qualities. That is pristine beaches with possibilities for relaxed beach life, bathing and maritime outdoor activities. The small intimate fishing villages have provided the most necessary services in the form of shopping opportunities. Further, the area is located in the capital region of Denmark which boasts the country's largest population. In combination, these conditions have created the framework for attractive excursions, holiday experiences and recreational developments on the north coast of Zealand. Further, this coast has historically been the preferred swimming location for the royal family of Denmark, which adds to the prestige of the coastline.

Since the massive expansion of summer houses in the 1950s, 1960s and 1970s, there has been a focus on coastal protection. This reflects the desire to counteract the natural erosion on the coast, e.g. the

erosion of sandy cliffs that has historically dynamically changed the coastline and provided large quantities of sand sediments to be deposited along the beach and creating wide sandy beaches.
Because of the interests of the new landowners (i.e. the cottage owners), the coast has been protected locally by hard coastal protection measures such as boulders and rock walls along the foot of the cliffs (e.g. Vincent Sti at Vejby Strand), breakwaters (e.g. Liseleje), groynes (e.g. Tisvildeleje) and concrete flood walls (e.g. Rågeleje). This has reduced sand erosion and hampered the natural deposition of sediments along the coast. This has resulted in narrower and stonier beaches and less attractive beach environments. At the same time, the interest for the north coast as a tourist destination has been challenged in the recent years (VisitDenmark, 2018), possibly because of new attractive beaches and bathing facilities that have been created in and around Copenhagen (including e.g. Amager Beach Park and the Harbour Bath at Islands Brygge), but probably also because the qualities of the coast as a beach, and hence as a recreational attraction, have been in decline.

In recent years there has been an ongoing and strong focus on finding the right methods for coastal protection, and the proper economic and responsible distribution of the task and cost between citizens, coastal landowners, landowners associations and authorities (Horten, 2016). The need for action was highlighted by the impacts of the storm event named Bodil in 2013. Currently, the project Nordkystens Fremtid (the future of the north coast) is being implemented which includes slope protection combined with sand nourishment on selected longer stretches along the north coast of Zealand (COWI, 2016b; Fig. 4.3).

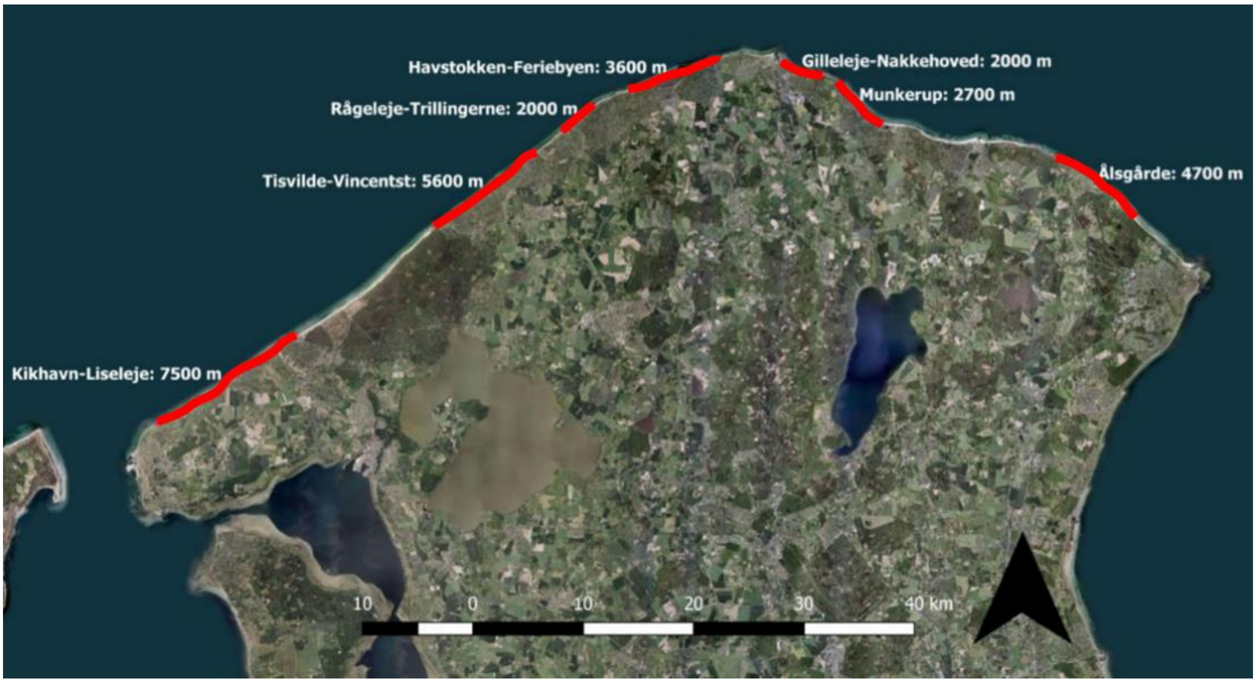


*Figure 4.3. Proposed interventions for the Nordkystens Fremtid project (source: COWI, 2016B).*

## Assessment according to the five chosen criteria

On the one hand, the north coast of Zealand has a strong brand as a pristine, attractive and prestigious recreational destination. On the other hand, individual actions and internal conflicts risk backlashing the region as a whole. The possibly egoistic, fragmented and opportunistic actions that are initiated at the lot and neighbourhood levels to combat dynamic coastal change risk exaggerating the negative impacts and impede holistic and coordinated responses that address integrated coastal management at the regional level in a more systemic manner.

**Technical security**

Recurring annual sand nourishments in the range of 5 $m^3$ per meter of coastline at designated sites is expected to keep the status quo situation over the coming 50 years (COWI, 2016a). That is, to replenish sand loss from erosion. Adding 60 $m^3$ of sand per meter in year 1 will initially elevate the seabed along the coastline by approximately 0.3 meters and return to the current condition in approximately 35 years' time. Combining initial sand nourishment of 60 $m^3/m$ and ongoing sand nourishment at 5 $m^3/m$ per year will maintain the beach approximately 0.3 meters above the current level and thereby also accommodate potential increased erosion resulting from sea level rise. The total coastline in need of protection is 28 km. With a combined solution this will require 6,580,000 $m^3$ of raw materials to be sourced from the natural seabed further away from the shore. This amount of sediments is the equivalent of lowering the seabed by 2 meters across the 3,5 $km^2$ area of Disken in Øresund.

**Economic considerations**

Sand nourishment in north Zealand is estimated to increase the prize of summer houses located within 100 meters from the coastline by 23%-35% (Panduro et al., 2017). This is the highest increase in house prices among the four coastal regions studied in Denmark by Panduro et al (2017). The value increase resulting from sand nourishment in north Zealand is three times higher than in any of the other coastal regions and hence very significant. Further, sand nourishment is identified to have a positive impact on house prizes for summer houses located up to 300 meters from the coastline, though the relative value increase is declining with the distance to the coast (Panduro et al, 2017).

**Environment/Nature**

Sand nourishment is interlinked with sand mining. It is a linear 'Sisyfos' task that needs to be repeated year after year. Further, sand dredging in the sea may have detrimental environmental effects as the natural flora and fauna is heavily affected. Currently, the excavation of sand at Disken in Øresund is much debated among politicians, anglers and environmentalists in Denmark and Sweden (TV2 Lorry, 2018).

In the development of the current project, the grain size of the sand and cyclus of the local habitats has been the starting point for scheduling the development works. The size and the amounts of raw materials strengthen the need of profound evidence of the future for nature, both on the coastlines that will be exposed to construction activities, and the sites that are planned to be mining areas for the raw materials.

**Innovation potential**

The history of coastal protection along the north coast of Zealand is torn by conflicts, distrust and blame games among stakeholders. For 50 years, the engineers, landowners and municipalities have discussed coastal protection technologies, but decisions on wider integrated solutions have recurrently resulted in technological, political, financial or legal lock-ins (Hasløv and Kjærsgaard, 2014). Within the last five years, architectural renderings have provided visual scenarios of potential development trajectories which have gathered stakeholders around the table and served as a

cornerstone for constructive discussions. Further, the establishment of a project secretariat bridging the policies and priorities across three municipalities was key to secure the progress of the project.
A large innovation potential exists in the scale of the project and the perspectives for further development of nature restoration, revitalisation of the local life and combination of coastal protection and recreation. However, Nordkystens Fremtid is still in the early stages. The success of the initiative appears to be relying on the capacity and commitment of a few particular individuals or 'champions' involved in the management of the project.

**Coastal landscape**

The project is seeking to aim at partly restoring the original state of the area, and giving the possibility of later increasing the value of both nature and the recreation. An aim is to increase the presence of wide sandy beaches through sand nourishment, both one-off replenishments and ongoing nourishment.
The coastline is quite densely built up, which gives some good perspectives in terms of increased recreational potential, and on this background contribute with opportunities for development of the local economy around urban development and nature-based tourism.

**Key insights from Nordkystens Fremtid**

The coastal protection project is the largest, current Danish protection project regarding coastal erosion. It will be developed across three municipal administrative boundaries The project gives good potential for further development of nature restoration, revitalisation of the local life and combination of coastal protection and recreation.
The current project on the north coast of Zealand highlights the long-term challenges when we face a need of big scale shoreline protection: The bigger projects include not just a discussion of types of shoreline protection technology, but also the cumulative effects on nature on the construction site, and "off-site". What are the cumulative effects? What could be the alternatives? Is the project sustainable, both economically and in the broader perspective involving society, nature and recreation today and in the long-term perspective (e.g. 25, 50 and 100 years)?

## 4.4. Vejle


**Description**
Vejle is a fjord city located in the along the East coast of Jutland. Vejle's coastal morphology is a typical fjord inlet with a river in the hinterland. The tunnel valley is surrounded by hills to the north and south, which is characteristic for the moraine landscape of East Jutland (Jacobsen, 1976). Yet, the hills at Vejle are particularly steep by Danish standards. Etymologically, Vejle literally refers to a ford, i.e. a passage for wading through shallow waters (Historisk Atlas, 2018; Vejle, 2018). The earliest settlement was established on a small hill completely surrounded by waterways which on the one hand helped to fortify the town and on the other hand restricted the expansion of the settlement.
At present, the biophysical premises still affects the risk of flooding in Vejle. The town is recognized as one of 10 areas in Denmark that are particularly at risk of flooding (Miljøministeriet og Transportministeriet, 2011). The water system in Vejle is challenged by a combination of event types such as cloudbursts, high river flows, increasing groundwater levels, and increased sea levels in the fjord. The flood-prone area is defined as the entire low-lying part of the city in the valley between Vejle Fjord to the East and Vejle Ådal to the West, with the eastern part of the town severely exposed to storm surge and sea level rise. For Vejle, the potential damage cost is estimated to be 31,500 DKK per inhabitant (COWI, 2017).
Since Vejle is particularly exposed to a combination of flood risks, Vejle Municipality has initiated the development of a robust vision and development plan for the town. Some of the actions proposed to reduce the risk of flooding include: (1) Controlling excess water through new sluice and pumping station along with weirs and levees along canals (completed in 2016) (2) Delaying the water in the hinterland along the Grejs Å stream; (3) Creating a climate-boulevard as well as green and recreational areas in the city that also convey and detain water (Hansen and Sloth, 2017); (4) Improving the fjord promenade with coastal protection technologies. The flood protection measures aim to create added value and contribute positively to the development of the city as a whole. This assessment focuses on bullet point four, i.e. the coastal protection plans.

In order to protect Vejle from sea level rise, three scenarios for urban development and storm surge protection were developed and presented in 2017.

**Scenario 1: Green blue necklace.** This design suggests the creation of a 'necklace' of artificial offshore barrier islands in the fjord to the east of the existing coastline. Essentially an offshore dike solution, the design proposes a system of new green areas along a gently sloping dike landscape and the creation of new landmark buildings on the edge of the fjord.

**Scenario 2: Inside out.** This design proposes an elevated flood wall along the existing piers and closes to recent residential developments on the harbour front. Further, the flood protection wall connects the harbour from north to south.

**Scenario 3: Superdike.** This project suggests the implementation of a landscaped 'superdike' incorporating parking spaces and other urban design features in the interface between the city and the fjord. The dike is located close to the city centre and leaves the industrial port unprotected. The three design scenarios are illustrated in Fig. 4.4.

*Fig. 4.4. From left to right: design scenario 1(green-blue necklace), scenario 2(inside out) and scenario 3 (superdike). Source: Geertsen (2017)*

## Assessment according to the five chosen criteria

The three design scenarios provide a catalogue of ideas and solutions that can be compared to discuss benefits and costs of different options.

### Technical security

The scenarios reflect existing known technology from Denmark, Japan and the Netherlands including offshore barrier islands, floodwalls, superdikes and sluice gates. All three scenarios are designed to protect the city up to a +2.44 meter sea water level, which is expected to be the equivalent of a 100-year storm surge event in the year 2100. It should be noted that scenario 3 excludes protection of the industrial port pier.

### Economic considerations

If they do nothing, the urban flood damage costs resulting from a 100-year storm event in Vejle are expected to increase from currently 70 million DKK to DKK 1.7 billion DKK in 2100 (Geertsen, 2017). The budget for coastal protection reflected in scenario 3, which is the most expensive of the three options, is estimated to be in the range of 230 million DKK with new real estate projects serving as a lever for change (Vejle Amts Folkeblad, 2017).

### Environment/Nature

Scenario 1 expands the existing parkland at Skyttehaven into the fjord. The new landscape of islands may provide a terrestrial wildlife corridor connecting existing forest patches to the north and south of the fjord. However, if the artificial lagoon not properly designed, scenario 1 may also impose environmental challenges such as stagnant waters, eutrophication, odour problems and restricted fish passage between the fjord to the streams (Dolmer, 2017).

**Innovation potential**

Vejle is involved in multiple projects on sustainable development and climate change adaptation at the national and international level. This includes support from philanthropic trusts such as Realdania and the Rockefeller Foundation as well as collaboration with relevant Danish and EU-level funding agencies.

Representatives from Vejle Municipality continuously emphasise the need for mapping, planning, partnerships, investment, synergy and action as a means to develop holistic and sustainable solutions (Geertsen, 2017; Hansen and Sloth, 2017). Further, they highlight the need for flexible, dynamic and adaptive planning in contrast to a static and reductionist approach to climate change (Vejle Kommune, 2015). The three design scenarios are part of this explorative and discussion-oriented process addressing the coastal challenges faced by the city. The proposed creation of new landmark buildings by the fjord and the transformation of post-industrial port areas to new (flood protected) residential housing estates are indicators of the city's aim to meet multiple objectives concurrently. Hence, the integrated planning approach strives to increase the support from current and future citizens and optimise the potential revenue for potential investors in Vejle.

**Coastal landscape**

The new connection between the north and south improves the residents' access to and from the harbour and the surrounding urban districts and forests. Further, the green necklace may provide new options for angling, picnics and bird watching immediately next to the fjord. In addition, the green necklace proposes initial thoughts about the potential of aquaculture and recreational diving and floating housing in the new lagoon. The superdike reflects the potential of a multifunctional unit incorporating property development, parking and recreational urban landscapes in addition to the core function of protecting the city from storm surges. On the downside, all solutions obstruct the current striking vista from the city to the fjord and the coastal horizon, though all designs – and scenarios 1 and 3 in particular – suggest new possible interactions between the city, its residents and the water.

**Key insights from Vejle**

Vejle is located in a river estuary and challenged by multiple types of flooding induced by climate change including storm surges, sea level rise, rising groundwater, fluvial flooding from streams as well a flash floods from the surrounding steep hills. This has led to the initiation of a multi-level and cross-sectoral process of explorative, adaptive and communicative planning.

Three designs on storm surge protection have been developed to foster discussion on alternative urban development trajectories. The designs involve a combination of solutions which could potentially create added value to the city of Vejle. Yet, all designs are crafted around the same coastal protection technology, i.e. a dike which will keep the city dry up to a fixed crest height. A somewhat static response, a technological quick fix, to a dynamic problem linked to uncertainty. This impedes wider discussions on the process of building resilience in coastal settlements.

## 4.5. Gyldensteen Strand


**Description**

Gyldensten Strand is located on the northwest bound coast of Funen near the town of Bogense. The gross area is 616 hectares of former coastal lagune that during the past 150 years has served as farmland. The area was reclaimed as a polder landscape in 1871. The dikes were reinforced in the 1950s and the site was further drained off in the 1960s.
Historically, and prior to the land reclamation process, the shallow waters and lagoon system along the northern coast of Funen was an important habitat that supported a rich variety of waterbirds and aquatic animals (Aage V. Jensen Naturfond, 2018a; Aage V. Jensen Naturfond, 2018b).

A storm surge event in December 2013 damaged the dike between the former two islands St. Stegø og Lindholm. This event boosted a process toward taking the land out of production and setting up a managed realignment of the area. Back in 2011, the foundation Aage V. Jensens Naturfond had brought the area for this purpose.

The project is divided into three sub-sites reflecting different design solutions (Fig. 4.5.). The purpose of this is to monitor and analyse the different dynamic ecological changes over time and hence to research the potential of different realignment options for reclaimed land in the light of climate change and sea level rise. To the west, the large outer dike has been demolished to 'invite seawater back in' to a 214 ha restored coastal lagoon with shallow waters and a saline wetland environment. About 90% of the lagoon has an average depth of less than 1 m. At the centre, an existing inland dike has been reinforced, but pumping of water in the polder has ceased in order to create a 144 ha freshwater lake with reeds. Finally, to the east, a mosaic of existing small lakes, swamps and grazed wet meadows have been maintained though with slightly higher water levels than in the past.

The case description below focuses on the coastal lagoon located to the west and closest to town. The restored coastal lagoon serves both as a nature area and a coastal buffer area during storm surge events. The project was the first large-scale managed realignment project in Denmark and the largest in Europe. Further, it was the worlds' first project to allow permanent inundation of farmland (Kristensen, 2015).

The lagoon has three openings to the open sea at Lillebælt, the largest to the west and two slightly smaller openings to the east where the tide enters the lagoon. Hence, all migration of marine flora and fauna occurs through these openings. The process takes place either by drifting algae and aquatic animals actively searching the lagoon or by the passive passing of algal spores and larva floating in with the tide (Walløe Thorsen et al., 2016).


*Fig. 4.5. The lagoon at Gyldensteen Strand after the re-alignment project.*

## Assessment according to the five chosen criteria

**Technical security**

The level of protection is up to a height of +3.3 m DVR90 (Grontmij, 2014). A crest height of +2.92 m DVR90 is expected to protect the surrounding land against a 100-year storm surge in the year 2100 (COWI, 2011). The new and reinforced dikes have been subsiding by up to 1 meter within the first year after construction and as a consequence supplementary earthworks have been carried out (Grontmij, 2014). A total of 3.5 km new dikes have been constructed predominantly along the eastern and western shores of the coastal lagoon.

**Economic considerations**

The restoration project was made possible by funding from the nature conservation trust Aage V. Jensens Fond that has purchased the 616 ha of land and covered construction costs for the realignment of the area as well as eight years of ongoing monitoring and research at the site.

**Environment/Nature**

The goal of the project was to gain more and a more diverse nature, i.e. marine flora and fauna including larger wildlife such as fish and water birds.  The recolonization of the lagoon started with mobile animals such as Baltic prawns (*Palaemon adspersus*), sticklebacks (*Gasterosteus aculeatus*) and round gobies (*Neogobius melanostomus*), and subsequently buried animals such as Polydora and sandworms. Mussels were identified to have intruded the site in 2014 via pelagic larvae. Such invasion was later prevented by fringe worms. In the summer of 2014, a slower fauna development in the eastern part of the lagoon was due to suffocation from a massive cover of green algae, which is likely a result of the nutrient-rich environment created by previous agricultural production and fertilisation. The lack of equilibrium in the fauna is due to variations in algal growth and soil structure (Walløe Thorsen et al., 2016). From 2014 to 2016 the nutrient concentration in the lagoon was radically reduced from 316 kg N/ha in 2014 to 45 kg N/ha in 2016 which indicates massive uptake in the plants during the first few years. The situation is stabilised with lower levels of algae growth (Syddansk Universitet, 2016).

One of the design objectives was to reduce $CO_2$ emissions and to store carbon in the lagoon. The release of $CO_2$ from the 214 hectares was approximately 12,300 metric tonnes per year from the farmland prior to the planned inundation and approximately 3,200 tonnes per year after the project had been implemented (Walløe Thorsen et al., 2016). Sjøgaard et al. (2017) found that more than 90% of the organic carbon in coastal soils will be permanently preserved in the soil after inundation. After correction for differences in annual $CO_2$ emissions from agricultural production compared with emissions from the lagoon, the net $CO_2$ retention is expected to be in the range of 7,600 tonnes of $CO_2$ per year in the first few years (Walløe Thorsen et al., 2016). For longer-term net carbon benefits, larger microalgae including seaweed and seagrass need to settle in the lagoon. For more details, see Panadevo (2015).

**Innovation potential**

The project is one of the first of its character and has potential as a combination of nature restoration, reduction of $CO_2$ emission and a planned coastal retreat strategy.

**Coastal landscape**

The project restores the original states of the area and increases the value of both nature and the recreation. Within the first 1.5 years after the inauguration of the project, the site had received more than 90,000 visitors (Kristensen, 2015). This shows the destination value of the site. The site is situated very close to Bogense (distance less than 1 km), which gives some new perspectives in terms of recreational potential. The project provides new opportunities for the development of the local economy around urban development and tourism. As part of the project two parking spaces have been built, one at each end of the connecting road between the new lake and the lagoon. East of Langø a new bicycling path and footpaths connect the site to Lillebælt, and the new reserve in the eastern part of the area, as well as two viewpoints. Visiting Gyldensteen Strand can be combined with a visit to Æbleø which is a prominent nature reserve off the coast of Funen. Further, the north coast of Funen is famous for its angling locations and bird sanctuaries (Map - Seatrout Fyn, 2018).

**Key insights from Gyldensteen Strand**

Gyldensteen Strand showcases the short-term positive effects related to nature restoration, $CO_2$ reduction and recreational value. There is a big potential to further strengthen these parameters and explore the potentials of boosting the local economy through urban development and nature-based tourism. Further, the potential of nature restoration through a managed realignment process could be investigated further in a context with a higher building density, i.e. a more urban context.

The project is a unique and successful in its kind, also because the areas Gyldensteen Strand was bought with the purpose of implementing this type of research project and thus it is not a result of a particular political will in the local community or of collaboration across municipalities. The effect of implementing restoration projects in other coastal areas at risk in Denmark need to be carefully evaluated and planned in order to assess the points of weaknesses, strengths and adaptation to the local and territorial plans.

## 5. Discussion

The review of coastal protection technologies in a Danish and international context highlighted the following aspects:

**The dominance of hard protection technologies and a technical design approach.** The review shows a dominance of hard protection measures such as dikes, rock walls and sluice gates. 24 out of the 32 Danish coastal protection interventions included in the review reflected a hard coastal protection technology. The need for building flood control measures has changed over the years, from the expansion of farmland in rural areas to now encompassing more the need of protecting the built environment and cities in particular, from storm surge, sea level rise and coastal erosion.

The prevalence of hard protection technologies may partly be linked to the fact that these measures were historically built to reclaim new productive farmland. Based on the Dutch model of polders, the sluice and pumping stations were used to drain freshwater from agricultural marshland, and the sluice gates were closed during high tides to avoid seawater intrusion. In Denmark, there are approximately 150 of these land reclamation projects covering a total of 5% of the country's area.

The majority of the investigated coastal protection projects are implemented on the quayside or along the coastline. Few measures (1 out of 32 Danish projects, 2 out of 19 in the international context) focus on inland protection and have a bigger vision which involves planned realignment of areas at risk of flooding.

The hard protection technologies seem to focus on protection up to a given crest height, e.g. +2,9 m DVR90 or a 100-year storm surge event in the year 2100. This creates clarity of the design objective, but it may ignore risks that exceed the design criterion. For example, what happens in case of a 500-year event? What is the 'Plan B'? This approach to coastal protection can be characterised as *climate change adaptation as an event*, and end-point and an outcome in itself. It tends to be a one-shot operation that aims to fix the problem in one go. Yet, this approach can also reflect silo thinking, and hence be essentially mono-functional in the design and in the assessment criteria. Further, it can lead to sub-optimisations or remain symptomatic treatment that does not address the root of the problem. One example of this is to address coastal erosion along the north coast of Zealand by means of rock walls and sand nourishment (and sand dredging), rather than a planned retreat of settlement along the coastline. However controversial this option is in a political and social real-life context.

Conducting the review, it was relatively easy to identify data on the level of protection to sea level rise and details about the technical design and construction. It was harder to find relevant documents on e.g. the ecological impacts, the recreational value or the economic costs and benefits for society as a whole of different coastal development initiatives.

***Main findings:*** *Existing coastal protection measures emphasise a hard technical design approach.*

**The need for context-specific solutions.** The values and hence the local perspectives for coastal development are very different across Denmark. Both due to very different influences from natural conditions and wave forces, but also due to a concentration of property values in the towns and cities. In the coastal cities, it is often relatively easy to define the professional issues, geographical areas and solutions. In other words, technical experts can be relatively simply connected with the various disciplines and create targeted results. In rural areas, there is generally less private investments at stake and fewer direct stakeholders. In this context, a regional coordinating body or a network of stakeholders is relevant to facilitate the process moving forward. Therefore, it becomes critically important what processes, goals and methods are used to work on coastal development and coastal protection. Chapter 3 suggests three characteristic conditions and three corresponding types of project responses. That is, (1) the traditionally 'tame' construction project with off-the-shelf technical design solutions for a clearly defined smaller coastline facilitated by committed private stakeholders and the availability of a strong local economy; (2) the development project which is linked with a higher degree of technical, social and economic complexity, are more diverse set of stakeholders and spatial scales, but with a shared understanding of the need for action fostered by relatively strong economic interests; and (3) the planning project framed by a weak economy, limited impact costs, disagreement on means and ends and emerging civil disobedience and social conflict. On this basis, Denmark can be divided into a number of coastal catchments that share challenges and opportunities. With this type of regional mapping, an outline of the potential for meaningful collaborations on coastal security and coastal development across municipal and organizational boundaries can be created.

***Main findings:*** *A national mapping of the premises for coastal protection can help framing the problem and the problem-solving context which can develop partnerships and platforms for relevant knowledge exchange.*

**The need for holistic solutions.** The review revealed several projects combining hard coastal protection measures with wider urban and regional development goals. One example is Køge Bugt Strandpark. Whilst protecting the 400,000 residents living along the bay area from coastal inundation, the project created a new artificial landscape with attractive beaches, new lagoons and habitats, marinas and museums that have increased the overall attractiveness of the area and served as a catalyst for planned urban development south of Copenhagen. Further, the design of Køge Bugt Strandpark was inspired by the natural barrier islands that still remain along the bay just north of Køge. Though they remain at an early planning stage, the scenarios in Vejle reflect the ambition to link flood mitigation to urban development, with the idea of a super dike (crafted on the concept of super levees in Tokyo), and housing on new offshore barrier islands as prominent examples of this. The managed realignment project at Gyldensteen Strand involves the construction of new inland dikes close to the town and the main road, but the main purpose is to transform reclaimed farmland into a restored coastal ecosystem and to research and showcase how restoration ecology may be linked to carbon budgets and the promotion of tourism.

The appropriate solution reflects the local condition. There is no one-size-fits-all. As an example, coastal erosion on the north coast of Zealand predominantly affects the individual landowner with direct sea frontage – at least in the first place and in the short term. Over time, the problem (and importantly also the applied solutions) can have regional impacts, which is also reflected in the case of Nordkystens Fremtid, where reduced erosion of sand from cliffs has led to less sandy beaches further downstream. This appears to be a 'traditional' environmental problem with individual costs and collective benefits which commonly calls for a fairer distribution of costs, benefits and compensations among stakeholders and usually regulated through policy. The case of North Zealand is complicated by the fact that many landowners are not permanently residing in the area. Along the bay of Køge Bugt the challenge associated with storm surge is at a larger systemic level compared with the north coast of Zealand, also short term, because flooding of the densely built-up area may lead to a collapse of the system as a whole, e.g. resulting in inundated homes, blocked roads, power outages, closed schools, restricted food and water supply, et cetera. In this case, the need for communal and regional solutions is more prevalent and the distribution of costs between individual landowners and the wider public, effectuated through government taxes is likely to be less associated with conflict.

In the light of global sea level rise, the investments in coastal protection measures are expected to be massive at the national and international level. It is relevant to approach decision making in a holistic manner and aim for optimized synergies between multiple agendas and development goals. To support decisions, there is a need to develop tools to assess the feasibility of alternative solutions, combining technical safety, innovation potential, synergy effects and added values. Integrated modelling and selected pilot projects are expected to be relevant methods to explore and assess these potentials, e.g. through multi-criteria assessments or total-life cycle assessments of resource flows and costs.

The holistic solution may start with a broad set of goals and success criteria. The targets and 'key performance indicators' are starting to emerge in Denmark, when it comes to the biophysical conditions associated with climate change, e.g. the predicted level of sea level rise 50-100 years from now. There are also tools available to assess the impact costs associated with different flood events as well as the value of beautiful beaches on property value. However, the identification and definition of 'softer' targets associated with coastal development, such as recreational value, ecological benefits and life quality are lacking. Moreover, the current models tend to keep the built environment static, while the natural environment is subject to dynamic change. This is a paradox as the actual service life of buildings is commonly around 60-70 years (Donnelly Brandon, 2015; O'Connor, 2004), and hence the physical built environment has a potential to adapt gradually though urban transformation and urban turnover.

The projects reviewed in this report emphasize single element solutions, rather than wider systems of solutions. Planning integrated solutions should take into account several problems related to the urban and regional environments, e.g. what happens when the storm surge event occurs in combination with heavy rainfalls and a king tide? Are the settlements and communities prepared for this combined flood event? The planning of future coastal development projects should focus on the creation of synergy effects, add value in a broad perspective, and integrate with other plans. Building on the concept of integrated coastal zone management, planning should be seen as an active measure to facilitate sustainable development in coastal areas.

Taking the north coast of Zealand as an example, public authorities are facing serious challenges in relation to the long-term impact of the current situation. In this context, do we have to consider some projects as temporary (up to 25 years) and some projects permanent (50 years or more)? Will a new distinction between project types create the need of a new frame of understanding and practice and in the end, a new legislative framework that helps us evaluate activities as part of a more holistic and circular perspective on the coastline?

Nordkystens Fremtid seeks to balance the coastline between securing individual coastal properties against erosion and land loss with rock walls combined with sand nourishing. Subsequently, it is the intention that the recreational potential can be revitalized by developing the opportunities and activities that already exist along the coast. An alternative could be to think of coastal protection in a more challenging perspective, where parts of the existing settlements are abandoned, in order to replace or supplement new building types and new applications, which are more "climate-proof" and hence, better prepared for sea level rise and the forces of waves during heavy storm events. And with that simultaneously open up to other types of recreation and urban life than today, possibly with a cultural life along the coast is livelier all year round. This alternative may include consideration of the coast's natural geology, as an important design parameter and factor in relation to the disposal of coastal protection efforts. Further, this will factor in the turnover of the building stock, the actual service life of summer cottages and the dynamics of renovations and changing ownerships proactively regulated though building codes and local planning acts.

***Main findings:*** *Existing "off-the-shelf" coastal protection technologies should be supplemented with a broader view on the development of multifunctional coastal landscapes, e.g. in the form of solutions such as beach parks or coastal wetlands. The solutions should reflect the contextual premises of the site at the regional level.*

**Coastal development calls for thoughtful design.** The Danish coastline is the 'Mount Everest' or the 'Grand Canyon' of Denmark (Gram, 2014). The coastal landscape represents a valuable natural and cultural heritage that needs to be managed, protected, nurtured and utilised in a balanced manner with a view to the coming generations. The coastline is never static. It is continuously shaped by the wind, the waves, the currents, the sediments, the tidal changes, the vegetation and the animals that inhabit the coast. Neither is the coastline an entirely 'natural' landscape. For thousands of years, the coast has been moderated and shaped by human actions and peoples' interactions with the sea. The dynamics of coastal landscapes and the interactions between people and the environment along the coastline should be cherished. Further, coastal development should be considered as an artistic discipline similar to architecture and landscape architecture that strives for integrated solutions, is sensitive to the cultural and natural heritage, the 'spirit of the place', and which nurtures storytelling, craftsmanship and the application (or innovation) of appropriate technologies tailored to fit the specific conditions of the project site.

However, the projects reviewed show a striking absence of aesthetics and the human scale in coastal protection. Solutions in Denmark include boulders by Vincent Sti on the north coast of Zealand, Christmas trees along Erik's Hale on Ærø, skip waste containers (i.e. 'dumpsters') in Elsinore, and concrete tossed on the beach in Lønstrup. With the exception of Lemvig and few others newer harbour fronts and beach parks, as well as historical settlements and castles such as Ribe, Christianshavn, Vejle, Vordingborg, Kronborg and the terps by the Wadden Sea, the coastal developments are rarely linked to thoughtful reading of the landscape and an aesthetic consideration of the human scale and the sensual human interaction with the seashore. This is a paradox as Denmark is generally branded as a country with a strong design tradition (e.g. reflected in the internationally acclaimed architecture and furniture design from the 1950s and 1960s).

As a consequence, there is little consideration of the view to the sea potentially blocked by sea walls, little consideration of the social programming of the interface between land and sea, or little consideration of gradients of change. One reason for this could be the emphasis on technology (as stated above). Priority is on developing a solution that can protect the community up to a given statistical flood event. When this is done there is little time/money/interest in challenging the design and elaborating on the solution. The architectural design is reduced to an aesthetic task of styling (or masking or glossing over) the already consolidated technical design solution. It remains entirely as the icing on the cake. One way out could be to develop assessment tools that factor in the value of high-quality architectural design. Using cars as an allegory, the size of the engine and the fuel economy alone does not suffice to assess the value of a vehicle. Rather, the buyer's willingness-to-pay will also reflect parameters such as comfort, safety, choice of materials, colour, and brand value and resale prize.

Architects and the associated professions are trained in linking functional, recreational, aesthetic, environmental, social, cultural and economic interests into integrated designs. The human dimension is central to the development of high-quality spaces and environments whether experienced in private homes, in office buildings, parklands or public squares. The good design is developed in close dialogue with experts such as engineers, sociologists, medical doctors, ecologists or whichever profession is relevant to inform the integrated solution. Yet, as mentioned, thoughtful architecture is largely absent in coastal development projects.

The coastal protection itself is costly - which makes it even more relevant to aim for good and long-term results, both in terms of economy, nature and social considerations. Seeing coastal development projects as architecture is likely to be a key measure to achieve these synergy effects. Optimally, integrated coastal design is created on certain coastlines, which has the potential to be regarded as cultural heritage over time, by virtue of a strong interaction between technology and an attractive overall coastal landscape with space for tourism, nature and recreational experiences.

***Main findings:*** *Architectural design competences will help increase the overall quality and sustainability of coastal development projects and hence will help optimising the economic and societal benefits of the investments in coastal protection technologies.*

**The need to see coastal adaptation as a process, not an outcome.** As a result of climate change and global sea level rise, coastal development has reached the centre stage as a key agenda item across different tiers of government. The coastal zone represents a dynamically changing landscape. The built environment and the residents are at least equally dynamic and able to adapt. Yet, focus tends to be on the dynamically increasing sea level, how to 'hold the line' and keep things static in the context of change. It is about maintaining a strong focus on crest height rather than dynamic systemic change. Focus is on securing existing assets through one-off technological responses but fails to acknowledge and utilise the adaptive capacity of the social system on what is currently the dry side of the problem.

Referring to the terminology of Davoudi (2012) the dike reflects an *engineering resilience* approach that cherishes predictability, aims to keep the system at the status-quo, regards environmental change as a threat, and sees adaptation as an endpoint or an event (i.e. "*now* the city is adapted to climate change")(see also Liao, 2012; Fünfgeld and McEvoy, 2012) In contrast, *ecological resilience* allows for uncertainty, regards adaptation as an ongoing process and sees disturbances as learning opportunities (Davoudi, 2012; Fünfgeld and McEvoy, 2012; Liao, 2012). *Social-ecological resilience,* also referred to as *evolutionary resilience*, takes the discussion one step further and allows for more fundamental systemic transitions of the biophysical and social realms and their interfaces (Davoudi, 2012), e.g. questioning the environmental ethics and anthropocentrism of urban planning decisions (see e.g. Beatley, 1989).

At present, Danish municipalities seem hesitant to make decisions on coastal protection. They remain uncertain in terms of the legal framework, in terms of financing and the distribution of responsibility. They might not have the relevant in-house expertise to inform decisions and to proceed with the task. As a consequence, they are in doubt about which community engagement measures to apply and which potential conflict resolution mechanisms to prepare for at different stages in the planning process. This is new territory and many local governments are walking on thin ice when it comes to the important step of progressing from plan to action. This highlights the need for actions fostering knowledge development, a process of learning, and possibly institutional change in the social realm.

The cases of Vejle and Nordkystens Fremtid identify adaptation as an ongoing process and an opportunity for learning. In their attempt to build resiliency, Vejle emphasizes collaboration and knowledge exchange across sectors, between disciplines and in collaboration with civil society. Further, they highlight the need for adaptive planning. Nordkystens Fremtid, unites municipalities, the regional government, technical experts, decision-makers and residents in a coordinated joint effort for collaboration, knowledge building, and decision making that simultaneously meets short-term and long-term goals. A key issue is also to revolve around the legal opportunities and constraints in terms of financing, distribution of responsibility and technological responses to a dynamically changing coastal landscape.

To disseminate and scale up findings from Vejle, northern Zealand and elsewhere in a Danish context, the relevance of an innovation network such as "Vand i Byer" needs to be highlighted. To date, this network has around 10 years of experience in gathering actors from the public and private sector, including government officers, public authorities, manufacturers, consultants and academics, in a process that gets ' the whole system in the room' when it comes to urban water management. Utilising this existing network with more than 200 participating organisations and companies and expanding their activities to include coastal development seems a very relevant and a timely opportunity. On the one hand, this will boost the existing activities and expand the scope to include coastal development. On the other hand, this is an existing wide network of relevant actors that also has a consolidated track record of professional knowledge exchange, collective learning and professional training through institutions such as the Danish Institute of Technology, DHI, the Technical University of Denmark, Aalborg University and the University of Copenhagen.

***Main findings:*** *There is a unique opportunity to utilize the existing innovation network Vand i Byer (or a similar network) to facilitate joint learning and knowledge exchange across sectors and disciplines with the purpose of developing good, integrated and long-lasting solutions to coastal protection in Denmark and beyond.*

**Do we need a fundamental mind-set change?** The notion of 'holding the line', i.e. to avoid change and to protect current assets from inundation, usually means of dikes, sluice gates and sea walls, is the dominating paradigm in coastal protection. For centuries, land reclamation, the filling up of the sea, drained wetlands and regulated water levels have been exploited as technological measures to support peoples' livelihoods. The continuous optimisation of the engineered landscape has served to benefit people. This has generated new farmland, new ports, new city districts, even new countries. As an example, approximately 1/3 of Copenhagen is built on reclaimed land and former seabed. Consequently, the concept of a 'planned retreat' from the coast and the idea of downgrading productive farmland to unproductive wetlands (from a utilitarian anthropocentric perspective) is in many ways counter-intuitive. It might be contradictory to human striving and a possible evolutionary drive to optimise chances of survival as a species. Socially and psychologically it can be challenging to give in and to accept a more humble role of humans in relation to the natural environment. Arguably, this anthropocentrism may have deep historical, cultural and religious roots. See e.g. Genesis (1:28) "Be fruitful and increase in number; fill the earth and subdue it. Rule over the fish in the sea and the birds in the sky and over every living creature that moves on the ground."

To foster a discussion on the relevance of planned retreat in coastal areas in Denmark it is relevant to pose the question: do we need a fundamental mind-set change in our approach to coastal development? That is a change from a regime of control, stability and man-over-nature to a condition where people accept to be subjugated to the powers of nature, and hence where we develop our settlements with a more balanced view on the needs of humans and the environment compared with our actions in the past.

This is not a technological challenge. This is a mental challenge. Not only is this a challenge for the individual. It is a challenge for society as a whole. It is about world-views. About values and the surplus to broaden the discussion and the scope of options – to openly discuss the uncertainties of the scale, magnitude and pace of climate change – this might be a necessary step. The purpose of this is to challenge the current regime based on technology as a means to keep things static, to an open process of societal change and the changes in perceptions.

If this is the case, and by referring to the theory of evolutionary resilience (Davoudi, 2012) and sustainability transitions (Rotmans and Kemp, 2003), Denmark is in the very early stage of a potential regime shift in our collective approach to coastal protection and societal development in the light of sea level rise.

***Main findings:*** *For centuries, humans have subdued Earth. Consequently, planned retreat from the coast will require a fundamental mind-set change in society on the relationship between people and nature.*

**The need for integrated decision support tools.** This report lays the foundation for a more thorough quantitative analysis of future planned coastal protection projects, following the multi-criteria framework here proposed. In order to address several scenarios for coastal protection, the quantification of the criteria is necessary. Technical safety and economic feasibility are usually the first analyses carried out in the planning of a coastal project. The economic feasibility studies are the tools used for the financial sustainability of a coastal project and they are usually compared to damage costs (0-alternative). As discussed, in this report the "holistic" criteria of environment/nature, coastal landscape and innovation potential are equally important. In some cases, they might create economic added values, of which a quantification of those might be better used to inform decision making.

Investigating the future value of a place, and how this is linked to potential economic added values (e.g. real estate values; improved local economy) is certainly in need to be investigated. From an environmental point of view, there is also a need to assess the project at the early planning stage in a life cycle perspective, since the aim is not only to create sustainability for the present population but sustainable cities and regions for the coming generations.

The study by Hennequin et al. (2018) has investigated in a life-cycle perspective that there is a high probability that traditional hard engineering solutions (i.e. dike, dam) produce lower environmental damages than a do-nothing situation in specified locations in Denmark (e.g. Copenhagen). Their study has quantitatively proposed a general method to address sustainable flood management linked to flood risk assessment in coastal urban areas. A step forward could be to apply this method for assessing other technologies and coastal protection options: e.g. what is the environmental effect of a soft approach to coastal erosion against a 0-alternative.

In a holist view, the life cycle impact assessment should be integrated with a quantification of the innovation, the impact on coastal landscape, adaptation to the surrounding and culture of coasts.

***Final remark:*** *several factors need to converge and at different levels: technical safety, economic feasibility, improved nature and reduced environmental impacts, improved coastal landscape and* *potential innovation as well as political will, legislation, financial support from the stakeholders, and definitely a more holistic framework for the analysis of the different coastal protections.*

# 6. Conclusion

This study reveals the most up-to-date state of the art in relation to coastal protection technologies in Denmark and links to international cases. The analysis is built on previously published studies, in particular, the investigation carried out by Rambøll (2015). As a novelty, this study was aimed at studying the evolution of coastal protection technologies by analysing specific historical drivers (e.g. storm surge, coastal erosion) which have influenced and possibly sparked the implementation of protection projects (see Chapter 2). Additionally, the present study lays the foundation for creating a multi-criteria approach in the design and planning of coastal protection (see Chapters 3 and 4). The aim is to learn from the past in order to better plan for the future. In this report, four cases are analysed, two already implemented (Køge Bugt Strandpark and Gyldensteen Strand), and two which are at the planning stage (Vejle and Nordkystens Fremtid). The qualitative multi-criteria approach here proposed has helped in addressing key insights from the different projects, and also highlight how it is sometimes difficult to make these holistic assessments. As last, the review has made it clear, how working with an interdisciplinary team of authors can give a potential new dimension in the planning of coastal protection technologies, highlighting not only the need of creating robust technical engineering solutions, but also the need for better integration of architecture, coastal landscapes and the life quality of people.

The objectives of this report were to:

1. Trace the predominant trends in coastal protection technologies in Denmark and in an international context
2. Propose an integrated framework to assess and work with coastal protection in Denmark
3. Analyse selected coastal development initiatives in Denmark with a view to holistic coastal management
4. Discuss the potential limitations of current practices and outline future needs for research and development to better inform the planning and management of coastal areas in Denmark.

In conclusion, the following insights can be highlighted:

On objective 1, historic, recent and pipeline coastal protection technologies are reviewed and categorized according to the type of problem (sea level rise, storm surge, coastal erosion), the type of technology (hard structural protection, soft landscape-based protection, a combination of hard and soft measures, non-structural solutions), the time of implementation and the regional location in Denmark. The majority, i.e. 24 of the 32 Danish coastal protection projects reviewed in this study used hard structural technologies. Storm surge is the main reason for coastal protection (24 of 32 Danish projects), but sea level rise is emerging as part of the justification of more recent projects. Historically, the implementation of protection measures has often been sparked by extreme storm surge events. Internationally, there is a similar preference for hard structural coastal protection technologies, though there is an emerging interest in more multifunctional solutions and the creation of added values to the community

On objective 2, it is proposed to map coastal areas in Denmark in terms of property values, biodiversity, coastal dynamics and existing coastal protection measures as a way to group coastal regions and frame the problem context. The level of social and technical complexity and the economic capacity of the particular coastal region frames type of project processes and outcomes that can be expected to occur.

On objective 3, the already implemented projects at Gyldensteen Strand and Køge Bugt Strandpark and the planned initiatives along the north coast of Zealand and in Vejle are assessed in terms of technical security, economic considerations, environmental impact, the innovation potential and impacts on the coastal landscape. Holistic thinking and an emphasis on the planning and implementation *process* is identified as critically important to develop sustainable solutions that go beyond the goal of protecting existing assets.

On objective 4, the dominance of existing "off-the-shelf" hard coastal protection technologies should be challenged by a broader view on the development of attractive and sustainable coastal landscapes. There is a need for thoughtful design and holistic context-specific solutions. There is a need to see coastal protection and adaptation as a process rather than an outcome in itself and hence there is a need for innovation, experimentation and knowledge exchange across disciplines, regions and stakeholder groups. The development of networks and integrated decision support tools are part of this process.

This study was initiated to provide the state of the art of coastal protection in Denmark. During the time of writing and through recurring discussions among the group of authors, the scope of the report was expanded to also include a critical reflection on the predominant coastal protection practice in Denmark. As a result, this report works more as a discussion paper rather than a scientific report with a clearly delineated scope and thesis. This report is more concerned with the way we as society approach and conceptually *think* about coastal regions in the light of climate change, rather than trying to tame the problem and attempting to prescribe what to *do*.

It is time to challenge the status quo. It is time to be innovative (and concerned) in our approach to coastal development. Hopefully, this report can help to spark a discussion and frame some of the important tasks that lie ahead of us.

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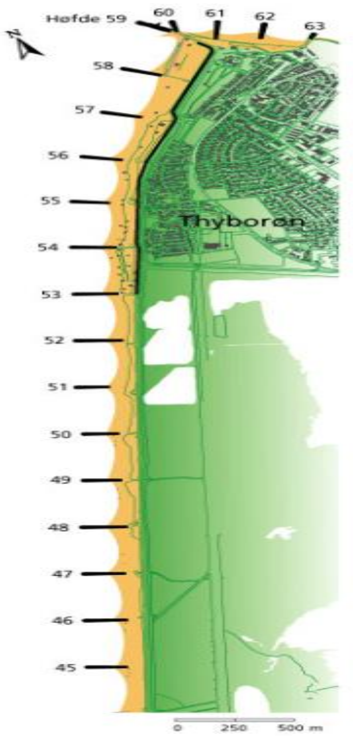
## Appendix

### A. State of the art of coastal protections technologies in a Danish context

#### Historical solutions

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **Coastal protection at Thyborøn (West Jutland)**:<br><br>**1. Groynes**<br>**2. Coastal feeding**<br>**3. Dike** | Combination of soft and hard solutions | Storm surge, Erosion | The Thyborøn channel was created as a result of the storm surge in 1862. The harbour was constructed later in the years 1914-1917.<br>1. The groynes prevent coastal erosion. They were built in the period 1875-1892. Each groyne is constituted of about 45,000 tons of concrete blocks and granite. The breakwater 59 is the largest, and it is 400 meters long. The groyne 59 is the only one made of more than 60,000 tons of concrete and granite.<br>2. To stop the natural backwardness of the coast, since the 1970s 2.5 million m$^3$/year of sand were pumped up from the seabed at 20 m water depth in the west coast from Agger to Hvide Sande. The costs for this solution were paid by the state, Ringkjøbing County, and the affected coastal municipalities.<br>3. In 1974-78, the sand dike in the west part of the city was reinforced with a coating of asphalt. Currently, the dike is covered with sand, and the asphalted road is on top of the dike. |  | [2] [3] |

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| **Dikes at the Wadden sea (Southwest Jutland):**<br><br>**1. Dike at Tønder Marsken**<br>**2. Højer sluice**<br>**3. Det Fremskudte Dike**<br>4. **Vidå sluice** | Hard | Storm surge | 1. The Tønder Marsken dike is the oldest, still existing dike built in the years 1553-56 from Højer over Rudbøl to Lægan and further towards south west. The road between Højer and Rudbøl was built on the old dike. After Tønder Marsken dike, other dikes were built at Gammel Frederikskog (1692), and Rudbøl Kog (1715). Their construction follows the storm surge occurred in 11-12 October 1634 which affected the Wadden Sea.<br>2. The Højer sluice was built in connection with a bigger dike construction (Højer dike) in 1861 built to protect Ny Frederikskog.<br>3. In 1981 the Fremskudte dike was built. The dike is about 12 m long, and 8 meter high.<br>4. In connection with the Det Fremskudte Dige, Vidå sluice was also built in 1981 and consists of three side chambers with a total width of 20 meters. Vidåen flows through the sluice. | <br> | [4][5]<br>[6][1]<br>[13]<br>[80] |
| **Ribe Dike and Ribe Kammersluse (Southwest Jutland)** | Hard | Storm surge | The dike is 15 km long and reaches 6 meters above the sea surface. Ribe Kammersluse was initially built instead to reply for the need for sailing, and it is currently operated in three modes: low tide, high tide, and storm surge (i.e. sea water level higher than 2.5 m above the mean sea level). The dike and the sluice were built between 1909-1912 after the storm surge event in 1909 and 1911, where Ribe was flooded. The area to protect corresponding to about 6800 hectares, divided into 850 landowners. The landowners offered to pay 675, 000 DKK, corresponding to 1/3 of the total construction costs. The rest was paid by the state. |  | [7] [8]<br>[9] |

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| **Køge Bugt Strandpark**<br><br>**(Zealand)** | Combination of hard and soft solution | Storm surge | This protection was built between 1976-1979. The artificial beach is 7 Km long. 3 Breakwaters were also built to hold the sand in place. To renovate the beach profile 5 million $m^3$ of sand, of which 2 million $m^3$ from the bottom of the sea, were used. The main purposes to build the beach park were: flood protection, increasing port capacity, create recreation and amusement place. |  | [11]<br>[12]<br><br>[1] |
| **Det Lollandske dige**<br><br>**(Lolland)** | Hard | Storm surge | The dike is the longest coastal protection project in Denmark less than 63 Km long, and it was established in the period 1874-1877. It protects the area from Nakskov Fjord to Keldskov at Errindlev. The dike occurred as a result of the storm surge of November 13th, 1872. It is about 5 m high above daily water. It protects a total area of about 70 km2. Today, the dike is equipped with 8 pumping stations and sluices (ca. 20 sluices). |  | [1]<br><br>[66]<br><br>[70] |
| **Dunes at Hvide Sande and sluices at Hvide Sande**<br><br>**(West coast)** | Soft and hard solution | Regulating water level/navigat ion | In Hvid Sande there are two sluices: Gennemsejlingsslusen og Afvandingssluse. They played a very important role in the development and Hvide Sande city. The functions of the two sluices are different. *Afvandingssluse* has the purpose of regulating the water level and salinity in Ringkøbing Fjord, equipped with a lock to ensure navigation. The ***gennemsejlingsslusen***, also called ***Kammerslusen,*** has the purpose of creating connections between the sea and the fjord for shipping traffic. Kammerslusen was opened in 1931. Afvandingssluse was built in the years 1928-1931. It is constituted of 14 gates, each |  | [10]<br><br>[67] |

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| | | | having a width of 6.25 meters, and it can derive up to 1,500 $m^3$ of water per second. | | |
| **Costal protection of west coast:**<br><br>• **Breakwaters and beach nourishment** | Soft and hard solution | Erosion | The first breakwater was established in the 1870s in front of Bovbjerg, later extended to Bovbjerg massif and the two Limfjords strings, which partially solved the problem of coastal retreatment. From the 1990s also annual pumping of sand into the coast was carried out (2-3.5 million $m^3$ of sand). |  | [16] |
| **Værft(ø) - terps**<br><br>**(Nord/South west Jutland)** | Soft solution | Storm surge and high tide | Historically, shipyards were artificial elevations. Hills and coastal marsh areas which were not protected from dikes accumulated up to 4 meters high yards. In Denmark, there are about 60 shipyards, mostly in Southwest Jutland in Tønder and Ballummarsken. | <br>The picture refers to the shipyard in Hooge in Germany | [43] |
| **Gyldensteen Strand (North coast - Funen)** | Hard solution | Land reclamation | Dammed in 1871, reinforcement of the dike in the 1950s, drained in 1960s. (This solution is not used anymore). | NA | [68] |

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| **Amager strandpark (Zealand- København)** | Combination | Recreational project with a potential for coastal protection | Amager strandspark is a seaside public park, which was founded in 1934. In total it provides 4.6 Km of beaches. In 2005, an artificial island of the length of about 2.5 Km was added. The park has a Y shape in order to catch the waves originating from the South and the North. The park also provides other functions, e.g. recreation. It can be used for kayakers, swimmers, etc. |  | [1] [33] [41] [49] [73] [74] |
| **Vestamager dike (Zealand - København)** | Hard | Storm surge | In 1943 the dike in Vestamager was finally completed with a total length of 14 Km and a height of 4 meters. | NA | [75] |

## Recent solutions

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **Coastal protection of North Fyn: Sand nourishment and wave breakers** | Soft | Erosion | From August 1999 to September 2014, the coasts were nourished with almost 397,000 $m^3$ of sand. Afterwards, wave breakers were built in order to stabilize the beach. 11 (4+7) wave breakers were built in April 2004 and 4 in September 2009. |  Figur 4.48 Hofde 105, juni 2004, maj 2010 | [1] [2] [14] [15] |
| **Floodwall at Lemvig (MidJyttland)** | Hard solutions combined with recreational elements | Storm surge/ sea water level rise | It is constituted of a vertical concrete wall, established along the waterfront. The wall is 350 meters long and about 80-120 cm high. There are also a number of stairways and benches which hangs on the flood wall. The traffic can pass through the wall through intersections, which can be closed in case of high tide through sliding metal gates. It is a good example of a *multifunctional* solution since it protects from storm surge and at the same time provides other functions. Completion year: 2012-2013. |  | [1] [34] [44] [63] [76] [77] |
| **Fredericia C (South Jutland)** | Hard solutions combined with recreational elements | Storm surge/sea water level rise | The flood wall was built along the old harbour in combination with planted slopes areas. The solution creates a new recreational area along the waterfront, secures the access to the water, and protects against storm surge. The recreational area is constituted of open spaces and path areas. |   | [1] [34] [72] |

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| **Gentofte Kommune: Coastal road (Zealand)** | Hard | Erosion/ storm surge | Traditional flood wall along the coastline in Gentofte to secure the road and the area behind against erosion and floods. It is a curved concrete wall with a stoning in the front to reduce wave forces. |  | [1] |
| **Coastal protection in Copenhagen:**<br><br>**1.Amager strandspark**<br><br>**2. Vestamager dike**<br><br>3.**Avedøre Holme dike** | Soft and hard solution | Sea level rise/storm surge/recreation | 1. Amager strandspark is a seaside public park, which was founded in 1934. In total it provides 4.6 Km of beaches. In 2005, an artificial island of the length of about 2.5 Km was added. The park has a Y shape in order to catch the waves originating from the South and the North. The park also provides other functions, e.g. recreation. It can be used for kayakers, swimmers, etc. The beachpark is a recreational project with a potential for coastal protection<br><br>2. The new Vestamager dike is up to 5.8 meters high and 7 Km long. It extends from Kalvebodbroen to Kongelunden, behind the old dike and it protects West Amager. The old dike was reinforced from 3.5 to almost 5.9 m (2012).<br><br>3. The Avedøre Holme dike is 5.4 meters high and protects the urban area behind in Avedøre Holme. | <br>The figure shows “Amager strand park” | [1]<br>[33]<br>[41]<br>[49]<br>[73]<br>[74] |

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| **Nørresundby Waterfront (Aalborg-North Jutland)** | Hard | Seawater level rise and storm surge | The quay edge of 659 meters stretch has been increased twice since 2010, and it now reaches 1.90 meters above the daily water. The final increase of the quay edge and the implementation of recreation and esthetical elements (e.g. wooden terraces, a 3.5 meter wider promenade) was finalised in 2015.<br><br>The project was entirely financed by Aalborg municipality. |  | [35]<br>[37] |
| **Sluice, dike, and pumping facility in Aarhus** | Hard | Storm surge/sea level/cloudburst | Opened in 2015. The 3 main elements are: 1. Sluice: four gates of 2.5 m wide and circa 4.5 m high; 2. Pump station: which lifts the water from the river out in the harbour when the sluice is closed. This prevents floods coming from the water in the river. The pumping station is made of 5 pumps which can move almost 4 $m^3/s$; 3. Dike: 2.5 meter high. The facility has two functions: it protects from up to 2-meter water level, and it protects the city centre from the cloudburst. The cost of the project was 46 mio. DKK. | <br>*Oversigt over slusen og pumpeanlægget ved Aarhus Havn.* | [46]<br>[48] |
| **Sluice in Frederiksværk (Zealand)** | Hard | Storm surge/sea level | Inaugurated on November 11$^{th}$ 2017. The sluice port is itself 2.7 meters above daily water<br><br>The city council of Halsnæs Kommune has allocated 11.2 mio DKK for the sluice. Halsnæs water utility has co-financed 3.2 mio. DKK for the pumps and pumping station. |  | [69]<br>[71] |

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| **Combined sluice and pump station in Vejle** | Hard | Storm surge/sea level | Opened in 2016. It consists of a pump station made of 4 pumps, which can pump up to 7.5 $m^3/s$ and a sluice. Cost of the project: 45 mio. DKK.<br>It is a co-financed project. |  | [50] |
| **Buildings related solutions** | Structural-hard solutions | Storm surge/sea level | These solutions are established at the single building. An example in Denmark can be found in the city of Lemvig. The floor level of the buildings at the harbour is elevated and positioned at the same level as the flood wall. |  | [1] |
| **Water tubes** | Non-structural | Storm surge | The company "Environment Solutions" deployed almost 1 km of water tubes during the storm Egon in 2016 to protect areas at risk in Roskilde. |  | [35]<br>[85] |

## Pipeline projects

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **Vejle** | Permanent | Storm surge/sea level | Vejle is a city which is very exposed when at the same time there are extreme rainfalls and the water level in the fjord rises. Vejle municipality is working on three scenarios for storm surge protection: (1). Blue-green necklace; (2) Inside out; (3) Super dike. |  | [61] |
| **Odense** | Permanent | Storm surge/sea level | Three protection elements are planned:<br>1. Sluice at Stige Ø combined with dikes/floodwall: this project will secure up to 2.5 meters water level. The budget for this option is 40 million DKK and it is still unclear the subdivision of the expenditures between citizens and the municipality.<br>2. Dike in Seden Strandby: it will secure up to 2.4 meter water level; the expected cost is 5 million DKK.<br>3. Dike at Færgevej: it will secure up to 2.4 meter water level; the expected cost is 0.5-0.8 million DKK. |  | [78] |
| **København** | Permanent solutions | Storm surge/sea level | The outer solution can protect the harbour and the external coasts with dams, dikes, and gates across the harbour at Trekroner in the northern inlet to Copenhagen and just south of the highway bridge at Kalveboderne. Likewise, similar solutions have to be established at Nordhavn, Svanemøllen, and Amagers East coast.<br><br>Securing Copenhagen from the North is not so urgent since the risk of storm surge from North is limited. Moreover, it is more expensive than securing the city from South. |  | [33] |

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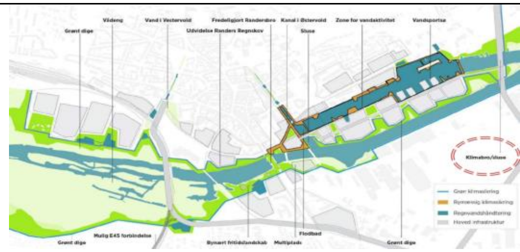
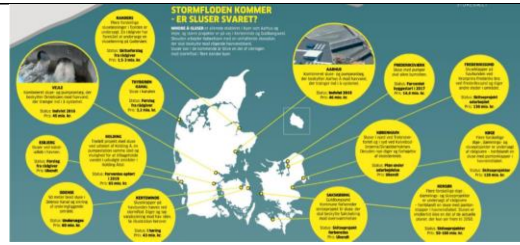
| **Randers** | Combination of solutions | Storm surge/sea level | Randers chose the scenario 4: "*Klimabroen og engbroen*". 8.8 Km of water line which must protect the city. Green dikes and sluices constitute some of the main elements. The aim is to protect the city from floods, to link the city to nature and to develop new synergies. The project has seen a high degree of citizen involvement and interested stakeholders. |  | [65] |
| **Kerteminde** | Hard solution | Storm surge/sea level | Combination of floodwall, sluices, and dike. Total estimated cost is 43 million DKK, of which: Realdania: 14.5 mio. DKK; Municipality: 3.9 mio. DKK; Forsynings og ledningsejer 5.7 mio DKK, private and companies will pay 17.8 mio. DKK |   | [38]<br>[39]<br>[40] |
| **Planned sluices in Denmark** | Hard solution | Sea level/storm surge | Dikes at a conceptual design phase: Frederikssund (sluice and dikes); Køge (dams, dikes, and sluices); Korsør; Salskøbing; Randers.<br>Proposal from consultants for Esbjerg and Thyborøn.<br>Expected construction in 2019 for Kolding.Consultation happening for Kerteminde. |   | [59] |
| **Assens Havn** | Combination of solutions | Storm surge/sea level | The base case scenario for flood control is an internal solution. This scenario consists of two alternatives and both ensure a safety level of 2.8 m (500 years return period):<br>Alternative 1: length of the protection 1785 m<br>Alternative 2: length: 2330 m.<br>The main elements of both alternatives are flood walls and dikes, and eventually rainwater basins. The solutions are focused on multifunctional principles.<br>Cost between 14.6-15.6 mio DKK. | NA | [64] |

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| | | | The long-term scenario for flood control in Assens Havn must protect against the worst predictable storm, and it is an external solution. The designed height is 3.5 m DVR90 corresponding to a 1000 years return period. The length of the protection is estimated at almost 1.8 Km. Estimated an overall cost of 39.5 mio DKK. General description of the solutions:<br><br>Dike (350 m), storm work (1400 m), gate (60 m) | | |
| **North Zealand coast** | Soft solution | Erosion | Zealand North coastline is around 60 Km. The project "Nordkystens Fremtid" has proposed a solution which is a combination of sand nourishment and slope protection technologies. | NA | [60] |

## B. State of the art of coastal protection technologies in an international context

### Historical solutions

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **Thames barrier in London** | Hard solution | Storm surge | It is one of the largest movable flood barriers in the world, in operation since 1984. It spans 520 meters across the river Thames and it protects 125 $Km^2$ of central London. |  | [17] [1] |
| **Eider Barrage in Germany** | Hard solution | Storm surge | It is the largest coastal protection structure in Germany. It was built to protect from storm surges from the North Sea. Opened in 1973. Currently, the barrage is 4.9 Km long, lies 8.5 m above sea level and 7 meters above the average high tide. There are five gates incorporated, each of 40 meters long. |  | [24] |
| **Oosterschelde barriers (the Netherlands)** | Hard solution | Storm surge | It is one of the main constructions for storm flood protection in Holland and the largest of the dams in the Delta works. This structure was opened on 4 October 1986. It closes *Oosterschelde* estuary from the North Sea. The sluice comprehends 62 openings with vertical lift gates, which is raised in the open state and lowered to close the barrier. |  | [1] [53] |

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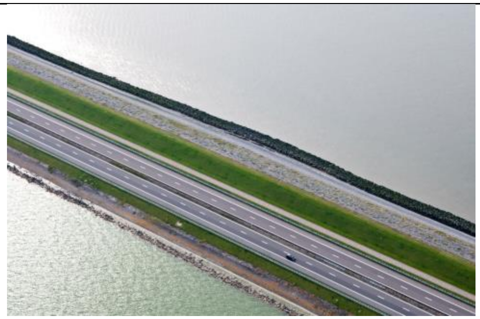
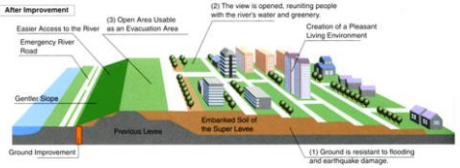
| **Maeslantkering storm surge gate (the Netherlands)** | Hard solution | Storm surge | This storm surge sluice is part of the Delta works and protects Rotterdam against floods. It was opened in on May 10, 1997. The sluice is built with two horizontal rotating gates, which in the open state are located in their dock along the side of the structure. |  | [1] [27] [54] |
| **Afsluitdijk (the Netherlands)** | Hard solution | Storm surge | It is a 32 km long dam, which is a part of the dam which delimits the freshwater lake Ijsselmeer toward the North Sea. It contains a highway. It is one of the primary high water protection of Holland. It was constructed between 1927-1932. |  | [1] [55] |
| **Hondsbossche en Pettemer Zeewering (the Netherlands)** | Combination of solutions | Storm surge | The dike is located near Petten, and it is 6 Km long. In 2014/2015 it was constructed a new dune and a beach area through sand nourishment, which currently is the primary storm surge protection in that area. Opened in 1880. |  | [1] |

## Recent solutions

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **Super levee in Tokyo (Japan)** | Hard solution | Storm surge | The super levee was built both for preventing the breakage of the existing traditional dike and to improve the access and the view to the coast. The dike constitutes an element which is completely integrated into the urban landscape. The super levee projects have been completed at 13 sites and two sites are still in progress. Most of the dwelling were relocated behind the super dikes, leaving the possibility for using the dikes for e.g. park. |  | [1]<br>[86] |
| **Saint Petersburg Flood Prevention Facility Complex (Russia)** | Hard solutions | Storm surge | Constituted of a series of 11 dams and locks. It can protect from flooding up to 5.4 m of water. It is made of 1,987,843 $m^3$ of concrete and 110,000 tons of steel. It was completed in 2011 at the cost of 3,85 Billion dollars. |  | [18]<br>[19]<br>[20]<br>[21] |
| **IHNC (Inner Harbor Navigation Canal Lake Borgne Surge Barrier) Lake Borgne Surge Barrier in New Orleans (USA)** | Hard solution | Storm surge | This concrete barrier was built by the US Army corps of engineers to protect vulnerable areas (e.g. New Orleans East, metro New Orleans). The construction ended in 2013. The barrier is almost 3 Km long, and it is made of concrete and steel The project can project against a 100-year storm surge. Estimated cost 1.1. Billion dollars. |  | [25] |
| **Katwijk coastal works project (the Netherlands)** | Combined solution | Storm surge | Parking area integrated into a hybrid solution where a recreational beach area is established. It integrates flood protection, parking, and recreation.<br><br>Construction: 2013-2015. |  | [1]<br>[35]<br>[57] |

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| **Dakpark, Rotterdam (the Netherlands)** | Combined solution | | A rooftop park incorporated into a dike. The old railway placement was converted into a shopping boulevard. Officially opened in 2013. The park is 1.2 Km long, 85 meters wide, and 9 meters high. |  | [35] [36] [58] |
| **Boulevard Scheveningen in the Hague (the Netherlands)** | Combined solution | Storm surge/sea level rise | Protect the city the Hague from floods. Interventions: 1. Seawall: 1 kilometre long and 12 meters high; 2. The beach was nourished with 2 million cubic meters of sand. 3. The reinforcement is fully underground and invisibly integrated into the new boulevard.<br><br>Floodwall with its associated beachfront, which is established as a part of renewed recreational shorelines. |   | [28] [1] |
| **Cleveleys in the North West England** | Hard | Sea level rise | It protects about 7693 properties. The whole promenade is designed for reducing flood risk and for being attractive and of public utility. The revetment has a stepped design very effective against floods which can also give easy access to the beach. The top section is flat and wide and built on two levels. There are also granite benches and concrete tables. The cost was £20 million, founded primarily by Defra with contributions from Environment Agency, European Regional Development Fund and Wyre Borough Council. It was officially opened in 2008. |  | [29] [30] [31] [32] |

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| **Examples of mobile solutions:**<br>**1. Grein, Austria**<br>**2. Stein-Krems, Austria**<br>**3. Dresden, Germany** | Non-structural solution | Storm surge (river) | Mobile barriers are types of barriers which can be deployed during a flood emergency and which can be removed after the emergency is passed.<br>Examples can be found in Austria and Germany.<br>Case 1: Mobile-bearing walls protecting the town of Grein. They are constituted of two main parts: permanently built solid foundations and removable mobile barriers. In Grein, the total barrier height is 3.6 m and the base wall is 1 m high. This mobile wall was completed in December 2010.<br>Case 2: Barrier holding back the Danube's surge in the village of Stein-Krems in Austria.<br>Case 3: mobile barriers deployed in Dresden. | <br>*Case 1: Grein in Austria*<br><br>*Case 2. Stein-Krems in Austria*<br><br>*Case 3. Dresden in Germany* | [35]<br>[83] |
| **Water tubes** | Mobile solution | Storm surge (river) | Water tubes are another example of deployable barriers. The tubes are filled with water, and they can stand the water pressure on one side.<br>In 2014, 400 meters of NoFloods Mobile Barrier were deployed in Mont de Marsan (France) to face the floodwater coming from the river Bidouze and the dike breakage along the train tracks. | <br> | [35]<br>[1]<br>[84] |

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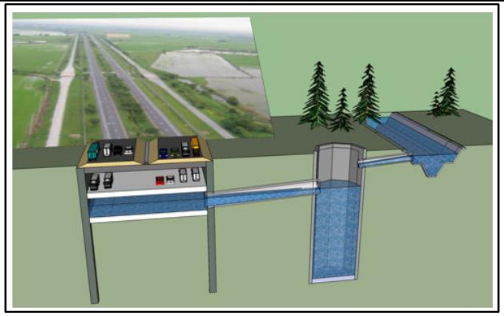
| **Managed retreat**<br><br>**(e.g. in UK and Netherlands)** | Non-structural - managed retreat | Storm surge/Sea Level Rise | It is not a real technical solution but an approach to plan and control how to return flooded areas to their natural state. This means that the defence structures are closed and buildings are moved to higher lying areas or adapted individually to withstand periodic floods.<br>1. The UK planned reversal along the banks for estuaries. This solution is part of major flood prevention schemes and allows for more efficient management. See Alkborough Flats.<br><br>2. Renewal of Noordwaard in Holland where reclaimed agricultural areas have been transformed into a floodplain. | <br>*Example of scheduled re-treat in Holland* | [1] [87] |
| **Building-related solutions (USA and Germany)** | Structural – hard solution | Storm surge/sea level rise | This type of solution focuses on protecting a single building. It can be done in connection with the building's renovation. This solution refers to:<br><br>1. Change in the foundation height of the houses (see Case 1: USA, Grand-Barachois) where the foundation of the house can be lifted up to a certain height or an elevated floor can be built instead.<br><br>2. Adapting the buildings to floods, e.g. by adopting gates which can close doors and openings in the masonry (see Case 2: Hafen City in Hamburg). | <br><br><br> | [1] |

## Pipeline projects

| Case | Type of solution | Problem | (Technology) Description | Photo | Source |
|---|---|---|---|---|---|
| **MOSE of Venice (Italy)** | Mobile gates | Storm surge | MOSE means in Italian “Modulo Sperimentale Elettromeccanico”, which is translated into English in “Experimental Electromechanical Module”. The project will protect the city of Venice from high tides of up to 3 meters. The project is constituted of gates which will be placed at the three inlets of Lido, Malamocco, and Chioggia. The 78 gates have the function to isolate the lagoon from the Adriatic sea during high tides. The gates at each inlet will function independently. They will be placed at the bottom of the sea and lifted up in case of high tide, by pumping compressed air into the gate structures. When there is no risk of floods, the gates will be filled with water and lowered into the seabed. The construction of the MOSE has started in 2003 and it is supposed to be finalized by 2018. The total cost is estimated at around 7 billion euro. |   *La laguna di Venezia e le tre bocche di porto* | [22] [23] [79] |
| **Tunnels to protect Bangkok (Thailand)** | Hard solution | Flood from Intense rainfall/drainage system not fully functioning | The city of Bangkok is planning to implement a system of tunnels called “Multi-Service Flood Tunnel System” (MUSTS). Flood water can be drained through a system of underground tunnels. The drained water could be also (re)used to generate hydropower. Besides draining flood water in a short time, this project has a minimal land appropriation impact and system of tunnels can be integrated with existing drainage systems. |  | [26] |
| **NYC Manhattan Seaport City (USA)** | Hard solution | Storm surge | This is a project proposal. A dike, where a tunnel is integrated into the dike core so that the traffic is held away from the terrain level. The dike is used as a park-like area or for recreational activities. |  | [1] |

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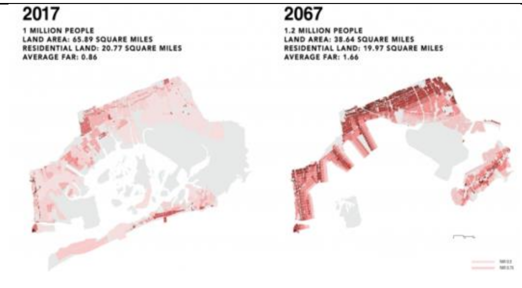
| **Dryline, New York (USA)** | Combination of solutions | Storm surge | The Dryline project won the global Bronze prize of the LafargeHolcim Awards in 2015. It comprises a 12 Km infrastructural barrier which will incorporate public spaces and high-water barriers. The high water barriers will also function as parks, seating, bicycle shelters, and skateboard ramps. The construction was established to start in 2017. |  | [35]<br>[42] |
| **Proposal for Galveston Island State (USA)** | Combination of soft solutions and recreational elements | Storm surge/Sea level rise | A proposal for Galveston Island State Park (entitled Sand + Storm + Sea + Strand) won the American Society of Landscape Architects' Professional Award of Excellence 2017. The design suggests to (re-)introduce a dynamically changing coastal ecosystem with migrating sand dunes, expanding salt marshes, rich in biodiversity and a centre for recreation and learning for visitors. |  | [81] |
| **Project on Long Island entitled: "Bight: Coastal Urbanism" (USA)** | Non-structural-managed retreat | Storm surge/Sea level rise | On Long Island, the widely published draft development plan (entitled Bight: Coastal Urbanism) suggests a managed retreat from the coastline. Over the coming 50 years, settlements in flood-prone areas are gradually phased out and compensated by new densified settlements on high ground and a realigned coastal landscape and buffer zone protecting the city against storm surges and extreme storm events |  | [82] |

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